

컨덕턴스 (CONDUCTANCE)

2022. 11. 10

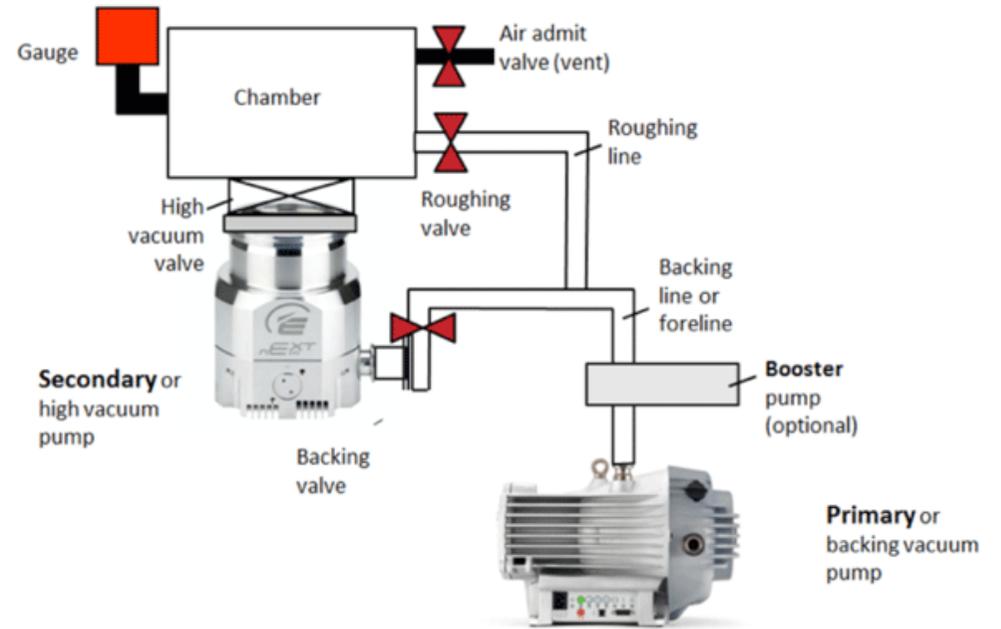
김효배

에드워드 코리아

차례

- I. 진공시스템
- II. 컨덕턴스 (Conductance) I
- III. 가스 흐름 영역 (gas flow regime)
- IV. 컨덕턴스 (Conductance) II

진공시스템



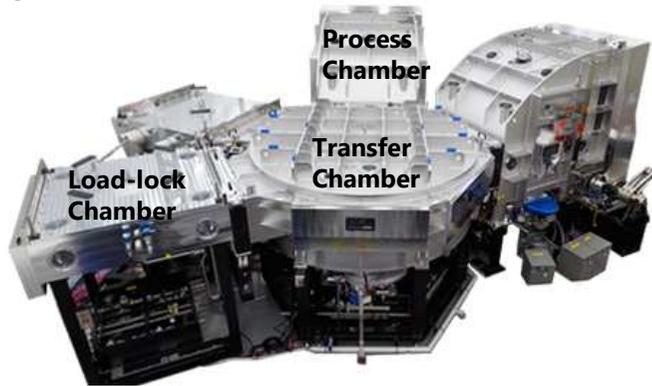
<https://vacaero.com/>

From 인상렬 박사 자료

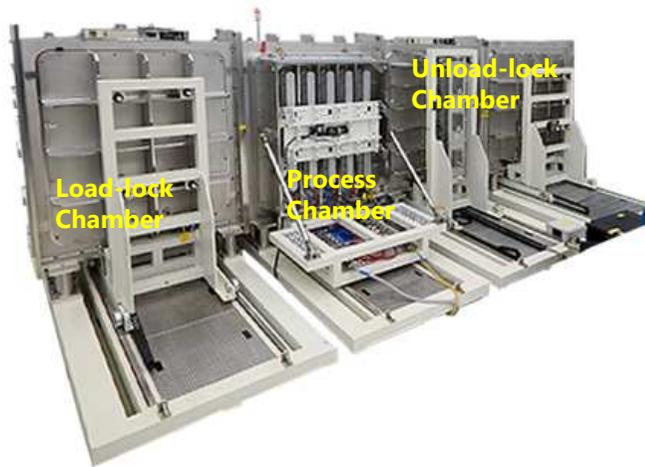
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진공챔버 - 진공시스템

Cluster Type



Inline Type



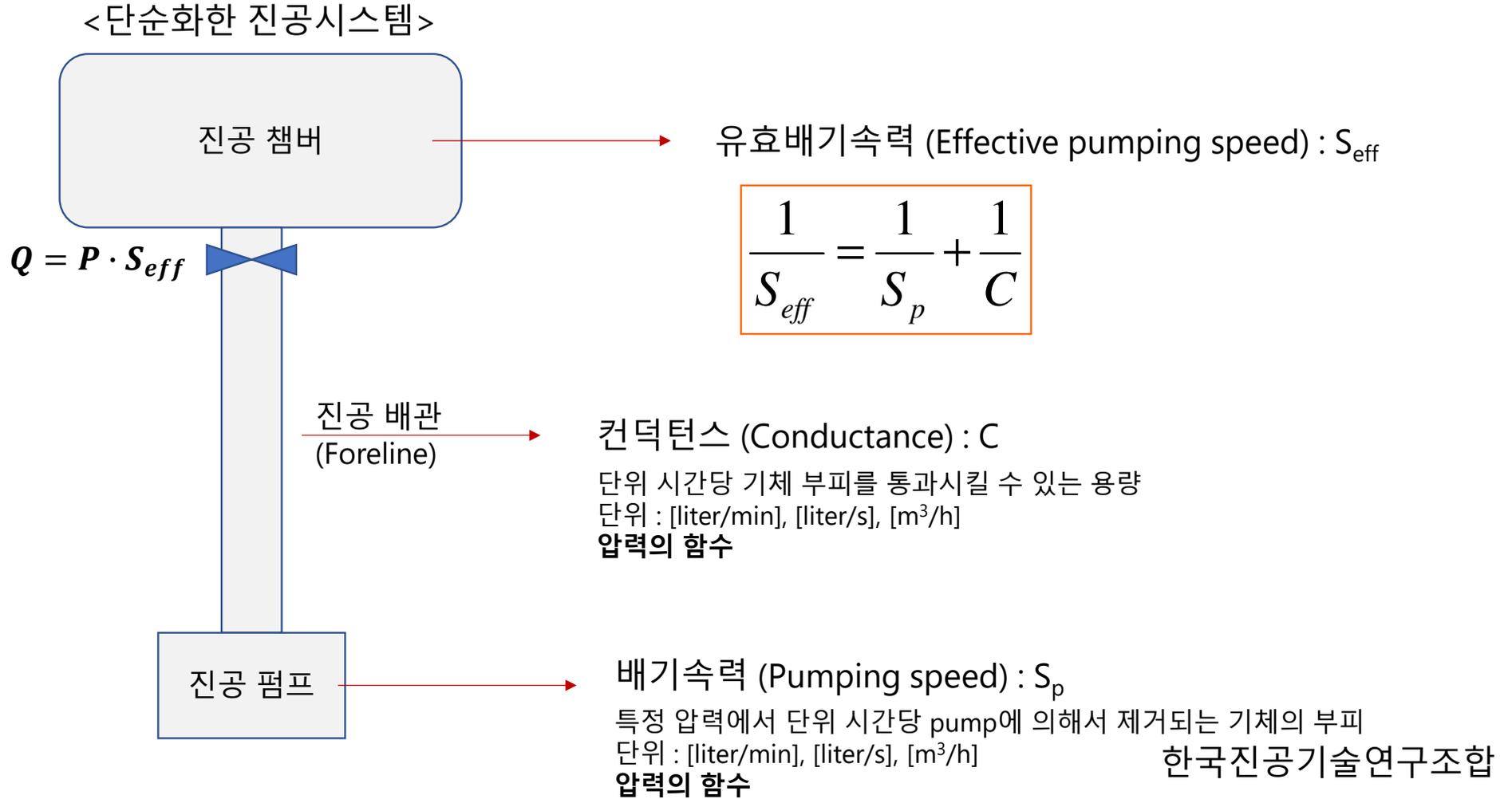
Load-lock chamber vs Process chamber

반도체 / 디스플레이 fab

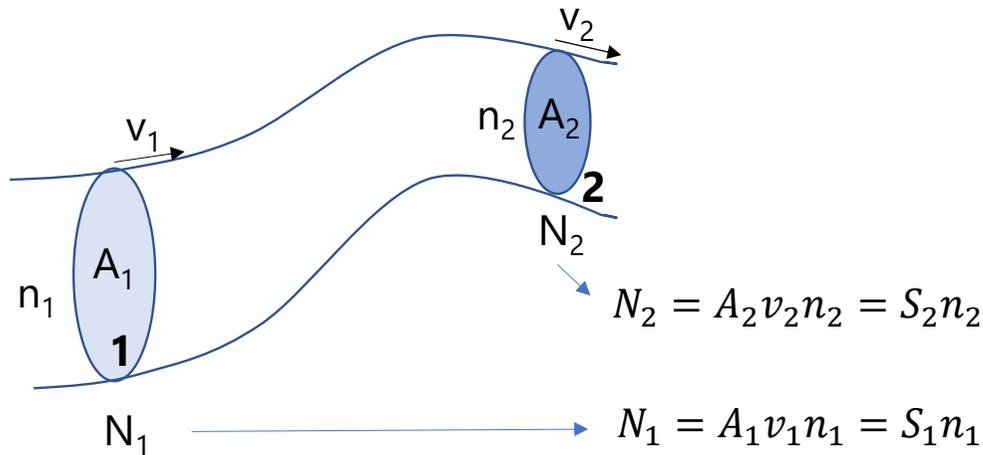


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진공시스템



Conductance



N_1, N_2 : 단면 1과 2에서 기체 분자수
 A_1, A_2 : 단면 1과 2에서 단면적
 v_1, v_2 : 단면 1과 2에서 기체의 속도
 n_1, n_2 : 단면 1과 2에서 단위 부피당 기체 분자수

이상기체 방정식 $PV = nRT = NkT$

In a permanent flow, $N = N_1 = N_2$ &

$$N = S_1 n_1 = S_2 n_2$$

분자밀도차 (압력차)는

$$N = C(n_1 - n_2)$$

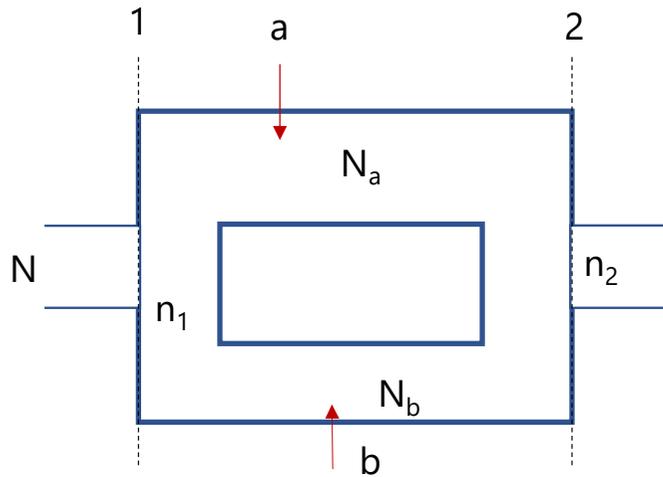
$$\frac{1}{C} = \frac{(n_1 - n_2)}{N} = \frac{1}{S_1} - \frac{1}{S_2}$$

$$\frac{1}{C} + \frac{1}{S_2} = \frac{1}{S_1}$$

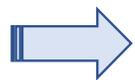
$$S_1 \rightarrow S_{eff}, S_2 \rightarrow S_p$$

$$\frac{1}{C} + \frac{1}{S_p} = \frac{1}{S_{eff}}$$

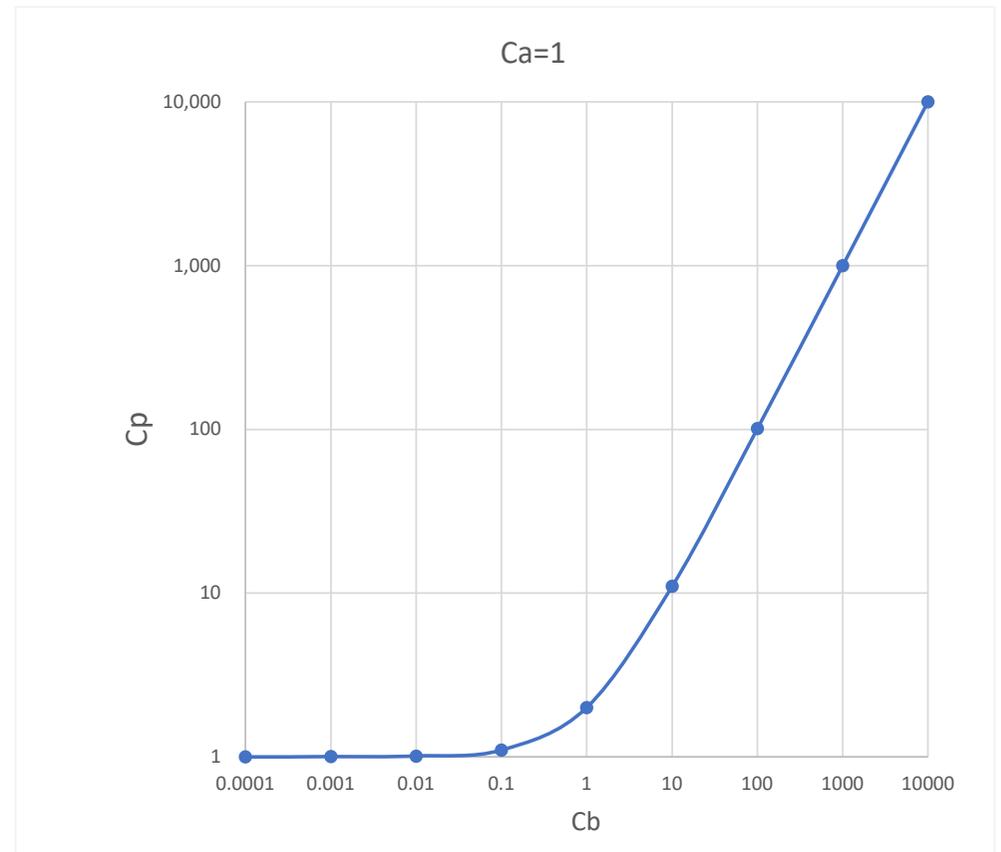
Conductance – 병렬연결



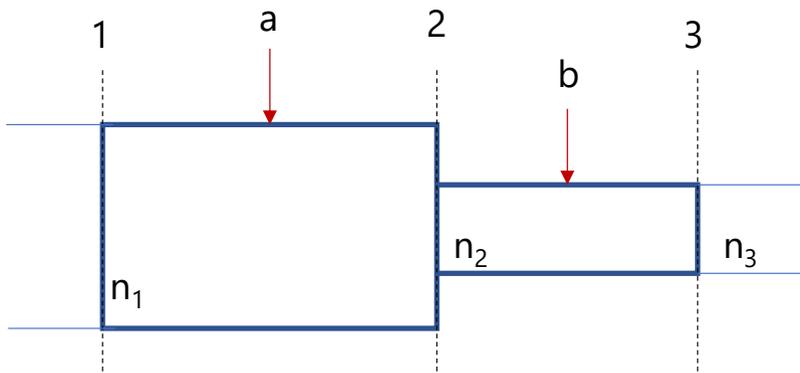
$$\begin{aligned}
 N &= N_a + N_b \\
 N_a &= C_a(n_1 - n_2) \\
 N_b &= C_b(n_1 - n_2)
 \end{aligned}
 \left. \vphantom{\begin{aligned} N &= N_a + N_b \\ N_a &= C_a(n_1 - n_2) \\ N_b &= C_b(n_1 - n_2) \end{aligned}} \right\} N_a + N_b = N = C_p(n_1 - n_2)$$



$$C_p = C_a + C_b$$

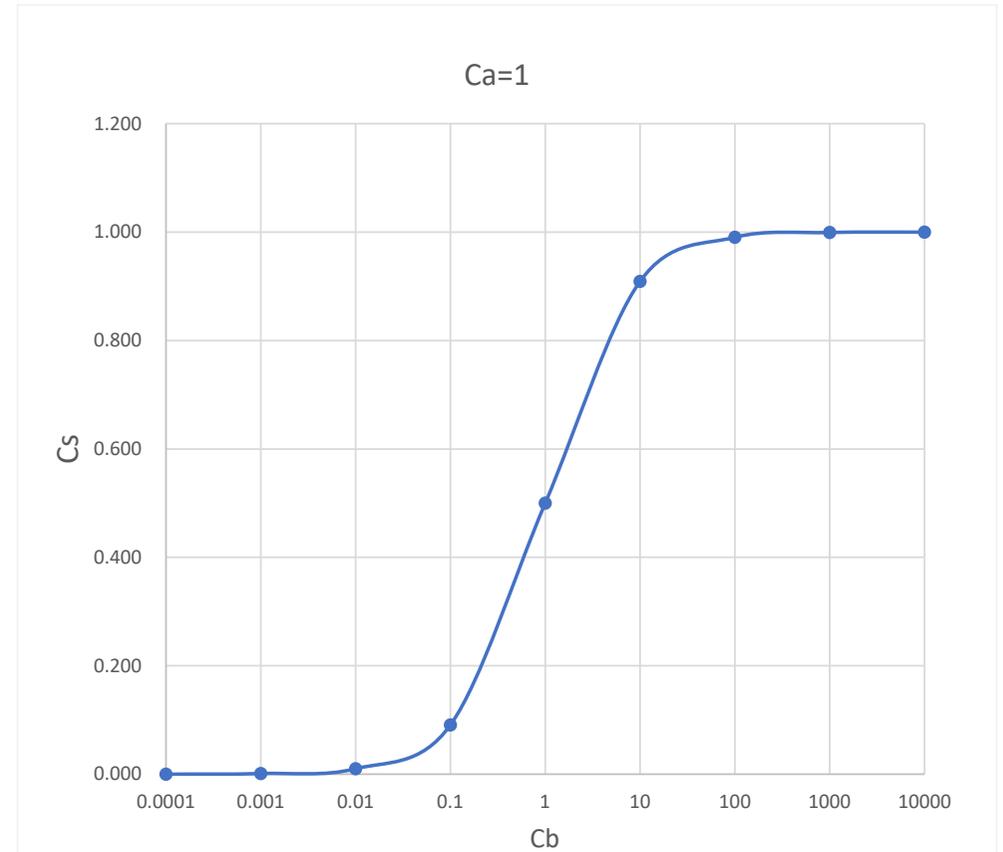


Conductance - 직렬연결



$$N = C_a(n_1 - n_2) = C_b(n_2 - n_3) = C_s(n_1 - n_3)$$

➡
$$\frac{1}{C_s} = \frac{1}{C_a} + \frac{1}{C_b}$$



예제

예제 1) 어떤 배관의 conductance가 200 l/s이다. 이 배관 두 개를 chamber에 연결하고자 한다. 직렬로 연결했을 때와 병렬로 연결했을 때, 각각의 경우 전체 배관의 conductance는 어떻게 되는가?

풀이 -

예제 2) 예제 1에서 직렬로 연결한 배관을 chamber와 pump 사이에 연결하였다. Pump의 pumping speed가 200 l/s라면 유효배기속력은 얼마인가?

풀이 -

예제

예제 3. 공정 압력이 1 Torr라면, 최대로 흘릴 수 있는 가
스량은 얼마인가?

풀이 -

단위변환

$$\begin{aligned} 1 \text{ Torr} \cdot \frac{l}{s} &= \frac{1}{760} \text{ atm} \cdot \frac{l}{s} = 0.0013158 \text{ atm} \cdot \frac{l}{s} \\ &= \frac{60}{760} \text{ atm} \cdot \frac{l}{\text{min}} = 0.0789 \text{ atm} \cdot \frac{l}{\text{min}} = 0.0789 \text{ slm} \end{aligned}$$

예제

예제 4. 공정 변화로 인하여 공정 가스량이 증가되었다. 공정 압력은 동일하게 1.0 Torr로 유지하지만, 최대 공정 가스량이 50% 증가하였다. 이 공정 변화에 대응하기 위해서 어떻게 해야 하는가?

1) 99,900 l/s

2) 199.6 l/s

풀이 -

예제

예제 5. 예제 4에서 공정 가스량 증가에 대응하는 방법으로 배관의 conductance를 변경하는 방법을 선택했다. Chamber와 pump 사이의 배관은 긴 직선 배관이고, 그것들의 위치를 변경할 수 없다면 배관의 직경은 얼마나 증가시켜야 하는가? 공정 가스는 20 °C air로 가정하자.

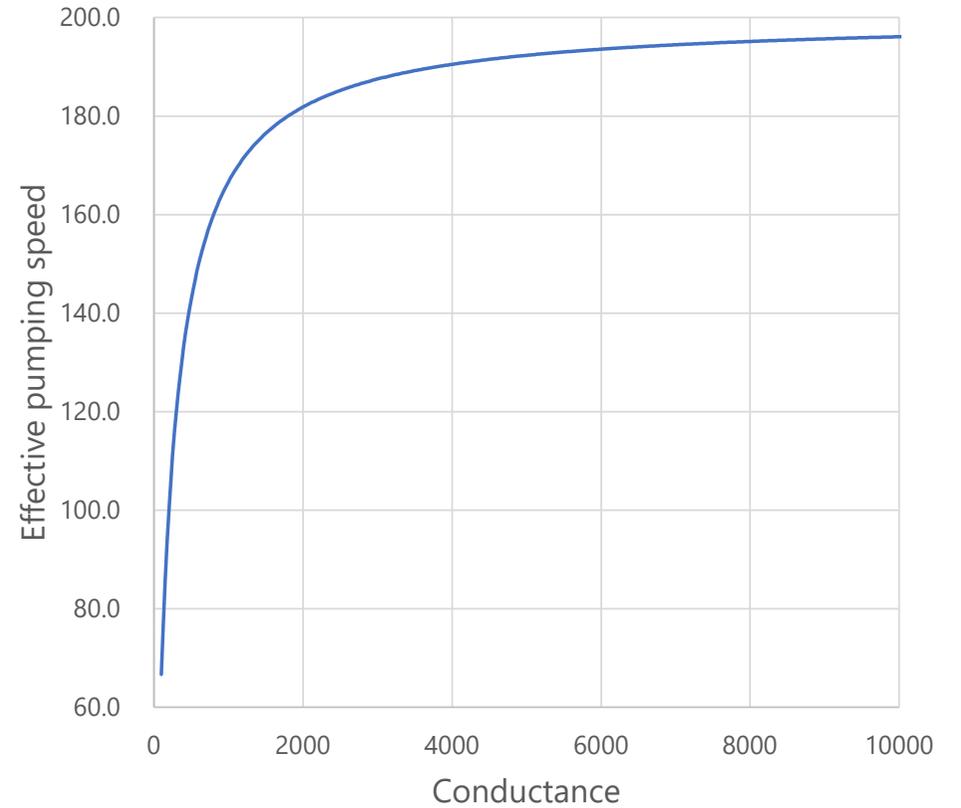
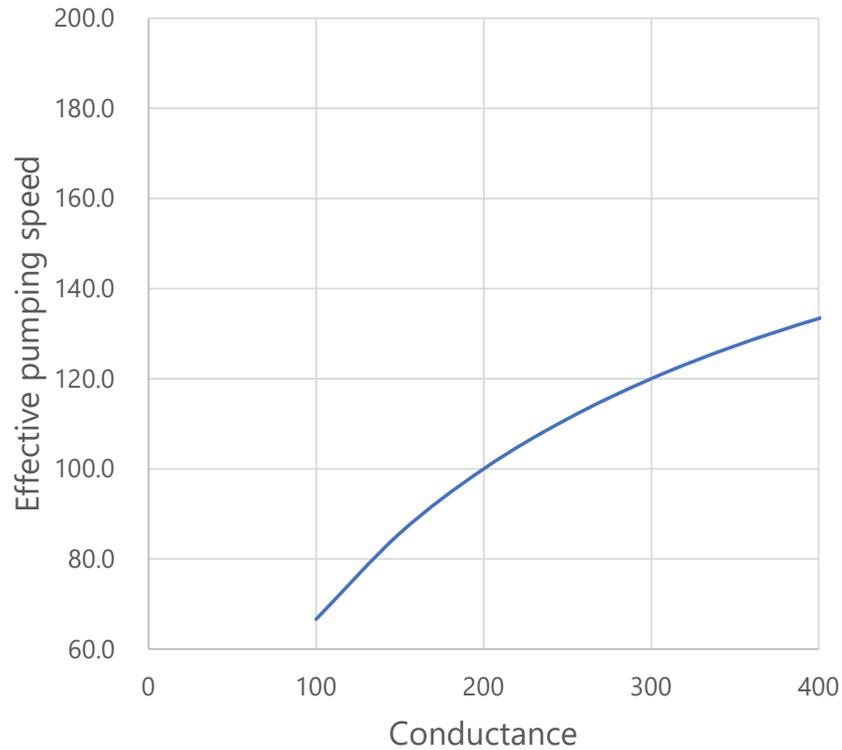
Hint. 배관의 conductance (1.1886)

$$C = 182 \left(\frac{D^4}{L} \right) \bar{P}$$

예제

예제 6. Foreline의 직경을 확대하면 배관의 conductance를 크게 해야 동일 압력에서 더 많은 가스를 처리할 수 있다. 왜 foreline의 직경을 크게 하지 않는 것인가?

풀이 -

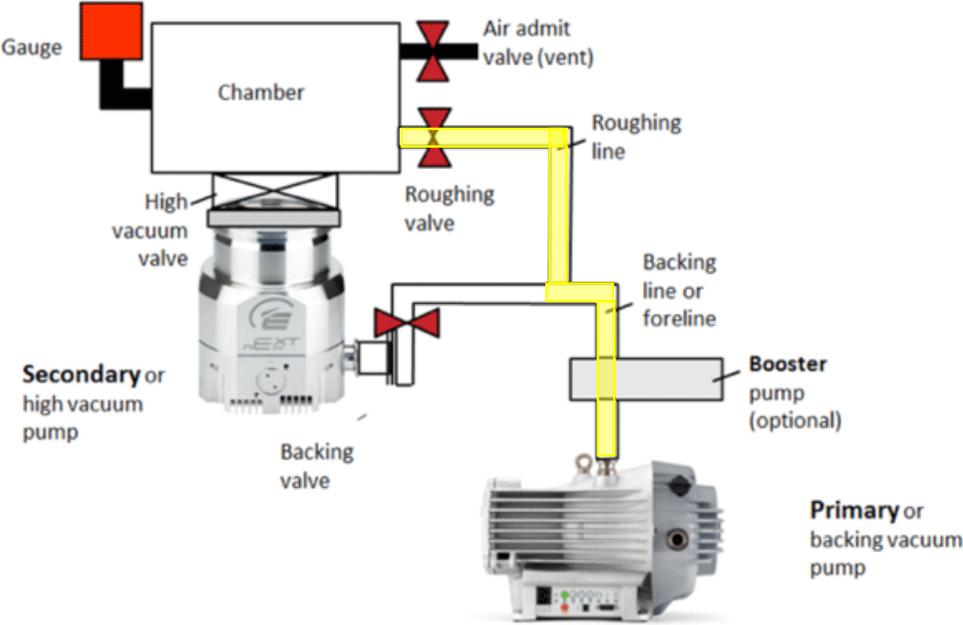


배관 규격

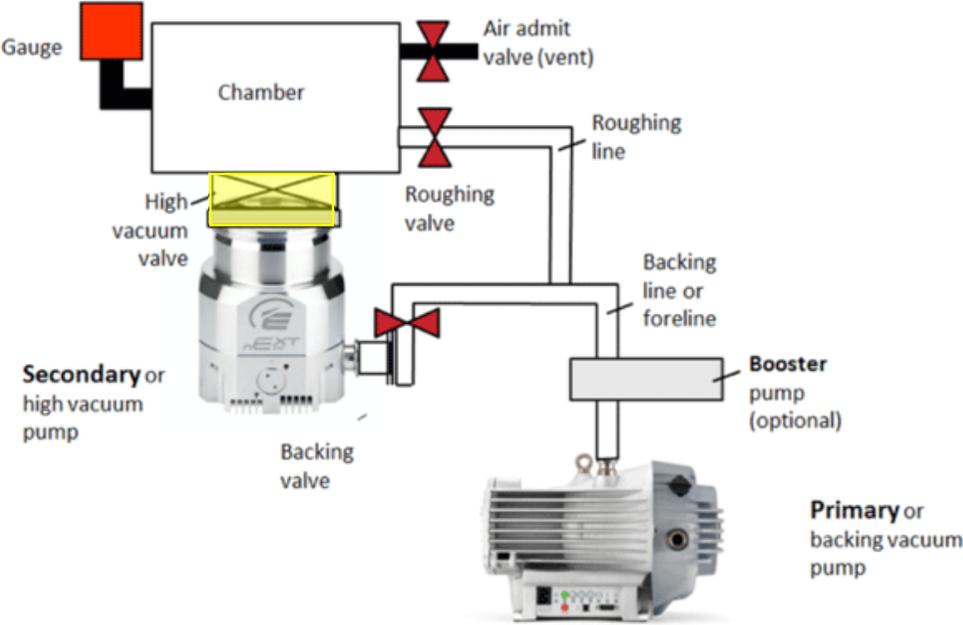
NW	내경 (mm)	ISO	내경 (mm)	JIS A B	내경 (mm)	VG	내경 (mm)	ANSI	내경 (mm)	DN	내경 (mm)
NW10	10			6A 1/8B	8.1	VG20	25.7	1/8"	6.833	DN6	7.82
NW16	16			8A 1/4B	10.4	VG25	32.5	1/4"	9.246	DN8	10.40
NW20	21			10A 3/8B	13.9	VG40	47.1	3/8"	12.522	DN10	13.80
NW25	24			15A 1/2B	17.5	VG50	59.0	1/2"	15.799	DN15	17.08
NW32	34			20A 3/4B	23.0	VG60	74.3	3/4"	20.930	DN20	22.48
NW40	40.5			25A 1B	28.4	VG80	87.1	1"	26.645	DN25	27.86
NW50	51			32A 1 1/4B	37.1	VG100	112.3	1 1/4"	35.052	DN32	36.66
				ISO63	70	40A 1 1/2B	43.0	VG125	136.8	1 1/2"	40.894
		ISO80	83	50A 2B	54.9	VG150	162.2	2"	52.502	DN50	54.76
		ISO100	102	65A 2 1/2B	70.3	VG200	213.3	2 1/2"	62.713	DN65	66.90
		ISO160	153	80A 3B	83.1	VG250	264.4	3"	77.927	DN80	82.80
		ISO200	213	90A 3 1/2B	95.6	VG300	314.5	3 1/2"	90.119	DN90	95.50
		ISO250	261	100A 4B	108.3	VG350	351.6	4"	102.260	DN100	108.20
		ISO320	318	125A 5B	133.0	VG400	402.4	5"	128.194	DN125	134.50
		ISO400	400	150 6B	158.4			6"	154.051	DN150	161.50
				200A 8B	208.3			8"	202.717	DN200	211.58
				250A 10B	259.4			10"	254.508	DN250	264.72
				300A 12B	309.5			12"	304.800	DN300	314.76
				350A 14B	345.6					DN350	346.04
				400A 16B	396.4					DN400	396.84

Conductance

저진공



고진공



Gas flow

State of the gas	Flow regime	Condition	
Viscous	Turbulent	$Re > 2100, Q > 200D$ (air)	$D/\lambda > 110$
	Laminar	$Re < 1100, Q < 100D$ (air)	
Transition	Intermediate		$1 < D/\lambda < 110$
Rarefied	Molecular		$D/\lambda < 1$

Reynold number ; $Re = \frac{\rho v D}{\eta}$

Knudsen number ; $Kn = \frac{D}{\lambda}$

ρ :기체밀도, v :속도,
 D :관의 직경,
 η :점성도,
 λ :평균자유행로 (mean free path)

Gas flow

Knudsen Number

Mean free path : λ

$$\lambda = 2.33 \times 10^{-20} \frac{T}{\xi^2 P} \quad [\text{cm}] \xrightarrow[20 \text{ }^\circ\text{C air}]{} \lambda = \frac{5 \times 10^{-3}}{P} \Rightarrow \frac{D}{\lambda} > 110 \Rightarrow \begin{cases} \frac{D}{\lambda} = \frac{DP}{5 \times 10^{-3}} > 110 \\ DP > 0.55 \end{cases}$$

T [K], P [Torr], ξ [cm]
diameter of molecule

Reynold Number

$$Re = \frac{\rho v D}{\eta} \xrightarrow[Q = \frac{PV}{t} = Pv \frac{\pi D^2}{4}]{\rho = nm = \frac{MP}{R_o T}} Re = \frac{MP}{R_o T} \cdot \frac{4Q}{\pi D^2 P} \cdot \frac{D}{\eta} = \frac{4M}{\pi R_o T \eta} \cdot \frac{Q}{D}$$

M=28.98
R_o=62.364 Torr liter/K
 $\eta=1.829 \times 10^{-4}$ poise

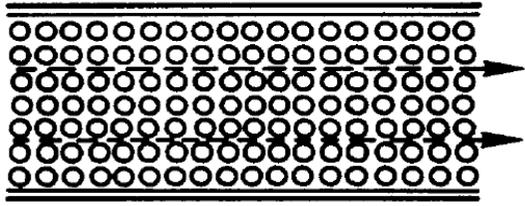
Re	$9.06 \times 10^{-2} Re$
2100	190.26
1100	99.66

For 20 °C air,

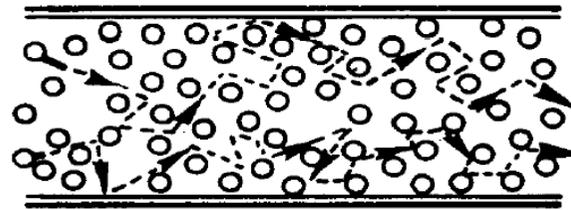
$$Q_{air} = 9.06 \times 10^{-2} Re D$$

D:[cm], Q:[Torr liter/sec]

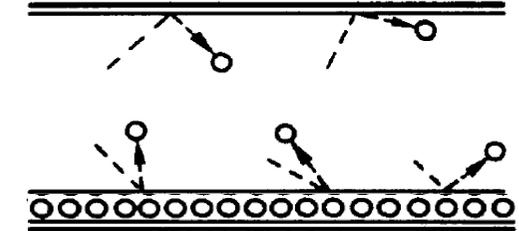
Gas flow



Laminar flow (層流:층류)



Turbulent flow (亂流:난류)



Molecular flow (分子流:분자류)
Knudsen flow

기체가 흐트러지지 않고 움직이는 것
유체의 가장자리가 매우 평탄
유속이 느림
기벽에서는 속도가 없지만, 기벽에 먼 곳에
유체 속도가 빠름

유동 중에 무질서하고 비정상적인 변화로
특징.
압력 및 속도가 시간과 공간에 따라
급작스럽게 변화

분자간 충돌을 무시할 수 있음
기체는 압력이 낮아짐
기체의 유속은 분자의 직진 운동의 속도와
관의 직경과 길이에 의해 결정
점성도와 무관

$$C = \frac{Q}{P_1 - P_2} = \frac{\pi D^4}{128 \eta L} \bar{P} = 182 \frac{D^4}{L} \bar{P} \quad \bar{P} = \frac{P_1 + P_2}{2}$$

20 °C air

$$C = 3.81 \left(\frac{T}{M} \right)^{1/2} \frac{D^3}{L} = 12.1 \frac{D^3}{L}$$

20 °C air

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Conductance

In a permanent flow, $N = S_1 n_1 = S_2 n_2$

$$\begin{array}{l}
 N = C(n_1 - n_2) \\
 \downarrow \times kT \\
 NkT = C(n_1 kT - n_2 kT) \longrightarrow NkT = \frac{NP}{n} = SP = Q = C(P_1 - P_2)
 \end{array}$$

$$PV = \frac{W}{M} R_o T \quad \left(\frac{W}{M} \right) \left(\frac{N_A}{V} \right) = n = \left(\frac{N_A}{R_o} \right) \frac{P}{T} \longrightarrow P = n \left(\frac{R_o}{N_A} \right) T = nkT$$

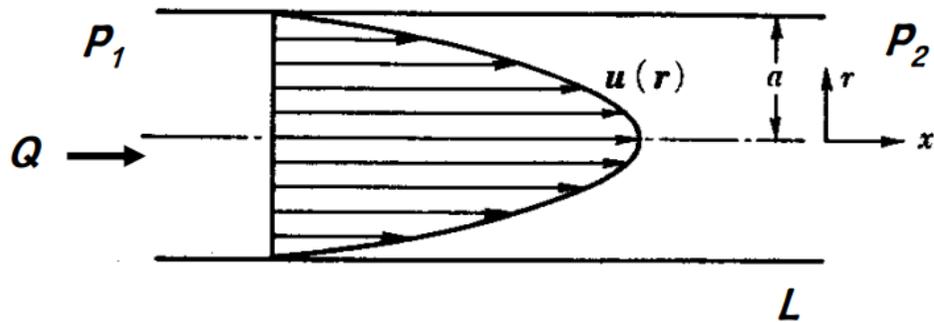
W : gas의 mass
 M : gas의 molecular weight
 R_o : ideal gas constant
 $= 8.314 \times 10^7$ erg/K·mole

N_A : Avogadro's number
 $= 6.023 \times 10^{23}$ molec/mole
 n : number of molec. per unit volume

$k = \frac{R_o}{N_A}$: Boltzmann constant
 $= 1.3805 \times 10^{-16}$ erg/K

Conductance – viscous flow

긴 원형 도관



Poiseuille's law

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

$$C = \frac{Q}{P_1 - P_2} = \frac{\pi D^4}{128\eta L} \bar{P} = 182 \frac{D^4}{L} \bar{P}$$

↑
20 °C air

For other gases, multiply

H ₂	2.046
He	0.918
N ₂	1.030
O ₂	0.904
Ar	0.815

단면형상	공역턴스 [m ³ /s]	20℃, 공기(M=28.98, d _m =3.76) [m ³ /s]
원통 (식 1-87)	$\frac{\pi d^4}{128\eta L} P_{av} = 4.522 \times 10^3 \frac{d^4}{L} \frac{d_m^2}{(MT)^{1/2}} (P_1 + P_2)$	$693.6 \frac{d^4(P_1 + P_2)}{L}$ d: 직경, L: 도관의 길이
사각	$\frac{a^2 b^2 P_{av}}{12\eta L} Y = 1.535 \times 10^4 \frac{a^2 b^2}{L} \frac{d_m^2}{(MT)^{1/2}} (P_1 + P_2) Y,$ $Y = \delta \left[1 - \frac{192\delta \left(\tanh \gamma + \frac{\tanh 3\gamma}{243} \right)}{\pi^2} \right], \quad \delta = \frac{a}{b}, \gamma = \frac{\pi}{2} \delta$ <p> ① $Y \approx \frac{1}{\delta + \delta^{-1} + 0.371}$ ② $\delta = 1, Y = 0.422$ ③ $1 < \delta < 3, Y \approx \delta \left(1 - \frac{192\delta \tanh \gamma + 0.00451}{\pi^2} \right)$ ④ $3 < \delta, Y \approx \delta(1 - 0.63\delta)$ ⑤ $1 \ll \delta, Y \approx \delta$ </p>	$2354.5 \frac{a^2 b^2 (P_1 + P_2)}{L} Y$ a, b: 변의 길이
이중원통	$\frac{\pi P_{av}}{128\eta L} \left[D_o^4 - D_i^4 - \frac{(D_o^2 - D_i^2)^2}{\ln \frac{D_o}{D_i}} \right]$ $= 4.522 \times 10^3 \frac{d_m^2 (P_1 + P_2)}{L(MT)^{1/2}}$ $\left[D_o^4 - D_i^4 - \frac{(D_o^2 - D_i^2)^2}{\ln \frac{D_o}{D_i}} \right]$	$693.6 \frac{P_1 + P_2}{L} \times$ $\left[D_o^4 - D_i^4 - \frac{(D_o^2 - D_i^2)^2}{\ln \frac{D_o}{D_i}} \right]$ D _o , D _i : 이중원통의 외경 및 내경
정삼각형	$\frac{9\sqrt{3} \ln 3 a^4 P_{av}}{20\eta L} = 1.578 \times 10^4 \frac{d_m^2 a^4 (P_1 + P_2)}{L(MT)^{1/2}}$	$2419.7 \frac{a^4 (P_1 + P_2)}{L}$ a: 변의 길이
타원	$\frac{\pi a^3 b^3 P_{av}}{4\eta (a^2 + b^2)^2 L} = 1.447 \times 10^5 \frac{d_m^2 a^3 b^3 (P_1 + P_2)}{(a^2 + b^2)^2 L(MT)^{1/2}}$	$2.22 \times 10^4 \frac{a^3 b^3 (P_1 + P_2)}{(a^2 + b^2)^2}$ a, b: 장반경 및 단반경
오리피스	(식 1-90) $1 > r > r_c, A\omega \frac{r^{\frac{1}{2}}}{(1-r)} \left(\frac{2\gamma}{r-1} \frac{kT}{m} \right)^{\frac{1}{2}} (1-r)^{\frac{1}{2}} r^{-1} \frac{1}{2}$ $\approx 91.185 A\omega \frac{r^{\frac{1}{2}}}{(1-r)} \left(\frac{2\gamma}{r-1} \right)^{\frac{1}{2}} (1-r)^{\frac{1}{2}} r^{-1} \frac{1}{2}$ $r \leq r_c, \frac{A\omega}{(1-r)} \left(\frac{2\gamma}{r+1} \frac{kT}{m} \right)^{\frac{1}{2}} \left(\frac{2}{r+1} \right)^{\frac{1}{2}} r^{-1}$ $= 91.185 \frac{A\omega}{(1-r)} \left(\frac{2\gamma}{r+1} \right)^{\frac{1}{2}} \left(\frac{2}{r+1} \right)^{\frac{1}{2}} r^{-1}$	$r > r_c, 770A \frac{r^{0.717}}{1-r} (1 - r^{0.286})$ $= 605d^2 \frac{r^{0.717}}{1-r} (1 - r^{0.286})$ $r \leq r_c, \approx 200 \frac{A}{1-r} = 157 \frac{d^2}{1-r}$ $r < 0.1, \approx 200A = 157d^2$ A: 단면적, d: 원형단면 직경 r: 압력비, γ: 비열비

Conductance – viscous flow

다양한 단면

Conductance – viscous flow

Orifice

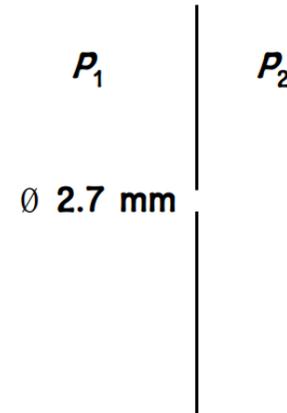
$$C = \frac{9.13A}{1 - \frac{P_2}{P_1}} \left(\frac{P_2}{P_1} \right)^{1/\gamma} \left\{ \frac{2\gamma}{\gamma-1} \frac{T_1}{M} \left[1 - \left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right] \right\}^{1/2}$$

For 20 °C air, $P_1 > 10 P_2$

$$C_o = 17.2 A \quad [\text{l/s}]$$

(A : orifice area, [cm²])

오리피스 예제



- 20°C, Air
- $P_1 > 10 P_2$, then $C \sim \text{constant}$
- $Pd = (20 \text{ Torr})(0.27 \text{ cm}) > 0.5$
∴ viscous flow
- $C_{o,\min} = 17.2 A \text{ (cm)}$
 $= 17.2 (3.14 \times 0.135^2)$
 $\sim 1 \text{ (l/s)}$

Conductance – molecular flow

긴 원형 도관

$$C = 3.81 \left(\frac{T}{M} \right)^{1/2} \frac{D^3}{L} = 12.1 \frac{D^3}{L}$$

↑
20 °C air

Orifice

$$C = \frac{Q}{P_1 - P_2} = 3.64 \times 10^3 \left(\frac{T}{M} \right)^{1/2} A$$
$$= 3.64 \times \left(\frac{T}{M} \right)^{1/2} A = 11.6 A$$

↑
20 °C air

예제

∅ 3.4 mm

• 20°C, Air

$$C = 11.6 A$$

$$= 11.6 (3.14 \times 0.17^2)$$

$$\sim 1 \text{ (l/s)}$$

Conductance – molecular flow

다양한 단면

$$C = \frac{8}{3\sqrt{\pi}} \left(\frac{2kT}{m} \right)^{1/2} \left(\frac{A^2}{BL} \right) = \frac{3.44 \times 10^4}{\sqrt{\pi}} \left(\frac{T}{M} \right)^{1/2} \left(\frac{A^2}{BL} \right)$$

Circular	Rectangular	Triangular	Annular
$A = \pi \frac{D^2}{4} \quad B = \pi D$	$b \leq a$ $A = ab \quad B = 2(a + b)$	equilateral triangle (a) $A = \frac{\sqrt{3}a^2}{4} \quad B = 3a$	Two concentric tubes with D_o & D_i $A = \frac{\pi}{4}(D_o^2 - D_i^2) \quad B = \pi(D_o + D_i)$
$C = 3.81 \left(\frac{T}{M} \right)^{1/2} \frac{D^3}{L}$	$C = \frac{3.44 \times 10^4}{2\sqrt{\pi}} \left(\frac{T}{M} \right)^{1/2} \frac{a^2 b^2}{(a + b)L} K$ $K \text{는 correction factor}$	$C = 0.413 \left(\frac{kT}{2\pi m} \right)^{1/2} \frac{a^3}{L}$	$C = \frac{\pi}{3} \left(\frac{kT}{2\pi m} \right)^{1/2} \frac{(D_o^2 - D_i^2)^2 K_o}{(D_o + D_i) L}$ $K_o \text{는 correction factor}$
For 20 °C air $C_{air} = 12.1 \frac{D^3}{L}$	$C_{air} = 30.9 \frac{a^2 b^2}{(a + b)L} K$	$C_{air} = 4.79 \frac{a^3}{L}$	$C_{air} = 12.1(D_o - D_i)^2(D_o + D_i) \frac{K_o}{L}$

길이 [cm], C [liter/sec]

한국진공기술연구조합

Conductance – molecular flow

짧은 원형 도관

1. 도관의 길이가 길면, C는 긴 원형 도관의 conductance
2. 도관의 길이가 짧으면, C는 aperture의 conductance

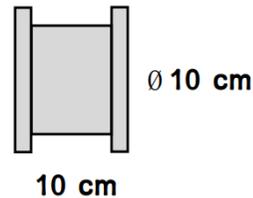
$$\frac{1}{C} = \frac{1}{C_o} + \frac{1}{C_L}$$

For 20 °C air

$$11.6A$$

$$= 11.6 \times 3.14 \times 25 = 910.6$$

$$12.1 \frac{D^3}{L} = 12.1 \times 1000/10 = 1210$$



$$\frac{1}{C} = \frac{1}{C_o} + \frac{1}{C_L} = \frac{1}{911} + \frac{1}{1210}$$

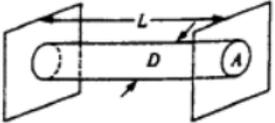
$$\therefore C = 520 \text{ l/s}$$

통과 확률 사용
 $C = 11.6 \text{ a A} = 468 \text{ l/s}$

Conductance – molecular flow



$$C = 3.64A \left(\frac{T}{M} \right)^{1/2} = 11.7A$$



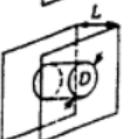
$$C = 6.18 \frac{A^2}{DL} \left(\frac{T}{M} \right)^{1/2} = 12.2 \frac{D^3}{L}$$



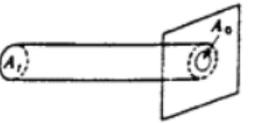
$$C = 3.81 \frac{D^3}{L} \left(\frac{T}{M} \right)^{1/2} = 12.2 \frac{(D_2 - D_1)^2 (D_2 + D_1)}{L}$$



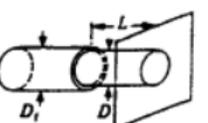
$$C = 9.70 \frac{b^2 c^2}{(b + c)L} \left(\frac{T}{M} \right)^{1/2} = 31.1 \frac{b^2 c^2}{(b + c)L}$$



$$C = 2.85D^2 \left(\frac{T}{M} \right)^{1/2} \left(\frac{1}{1 + 3L/4D} \right) = 9.14 \frac{D^2}{1 + 3L/4D}$$



$$C = 3.64 \left(\frac{T}{M} \right)^{1/2} \left(\frac{A}{1 - (A/A_0)} \right) = \frac{11.7A_0}{1 - A_0/A}$$



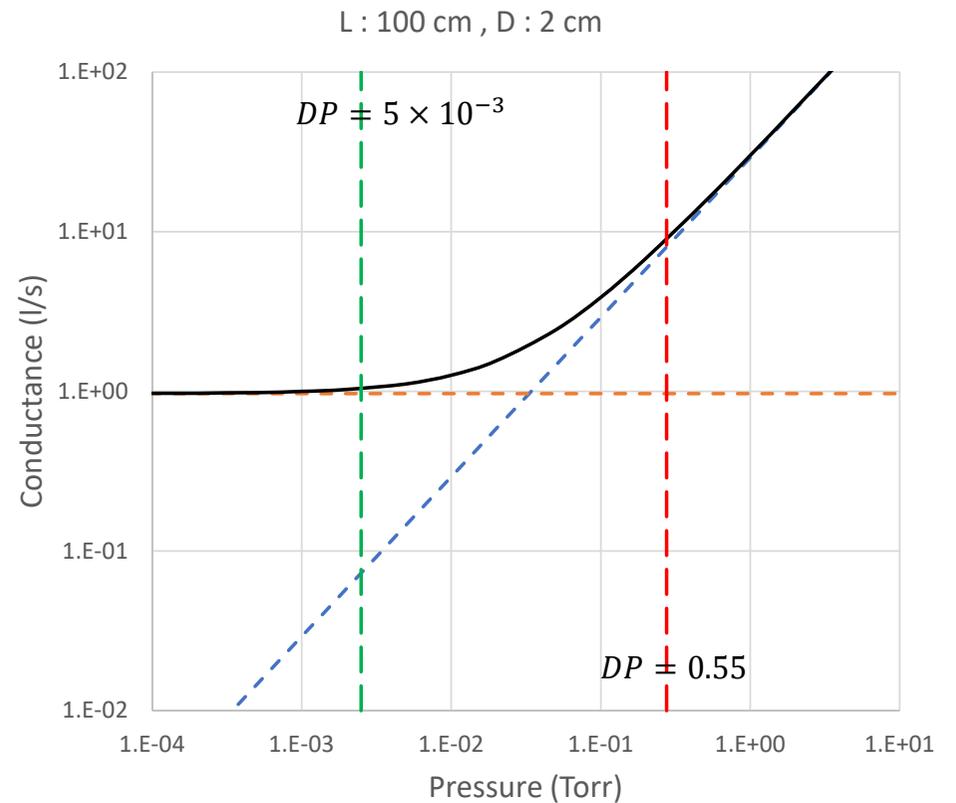
$$C = 3.81 \frac{D^3}{L} \left(\frac{T}{M} \right)^{1/2} \left(\frac{1}{1 + \frac{4D}{3L} \left(1 - \frac{D^2}{D_1^2} \right)} \right) = \frac{12.2D^3}{L \left[1 + \frac{4D}{3L} \left(1 - \frac{D^2}{D_1^2} \right) \right]}$$

Conductance – transition flow

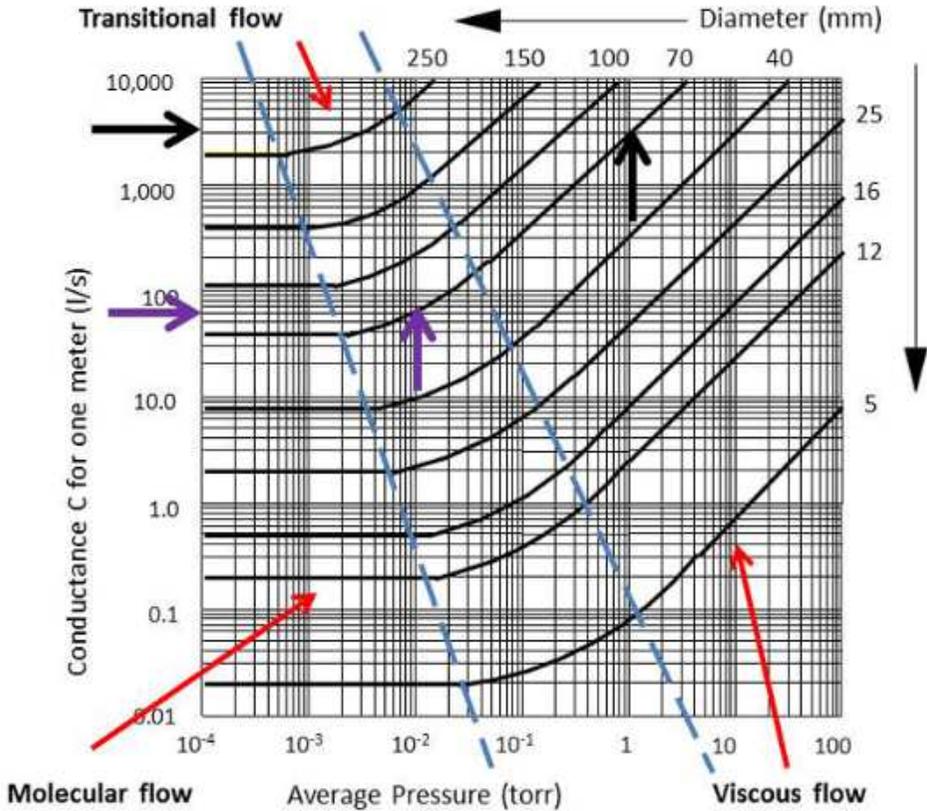
긴 원형 도관

$$C = \frac{\pi D^4}{128\eta L} \bar{P} + 3.81 \left(\frac{T}{M}\right)^{1/2} \frac{D^3}{L} = 182 \frac{D^4}{L} \bar{P} + 12.1 \frac{D^3}{L}$$

For 20 °C air

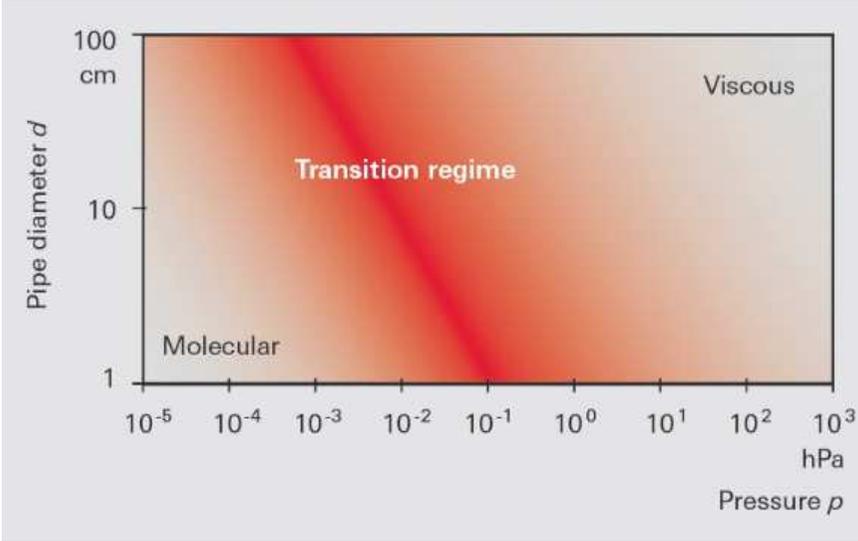


Conductance – transition flow



Conductance in 1 m long pipes

Flow ranges in vacuum as a function of P·D



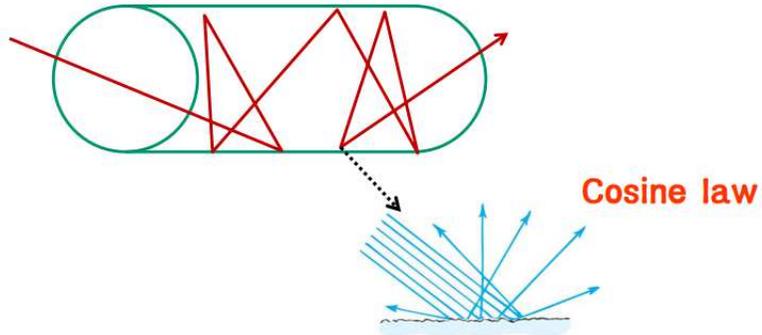
From Pfeiffer-vacuum.com

한국진공기술연구조합

From <https://vacaero.com>

Conductance – molecular flow

통과 확률



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

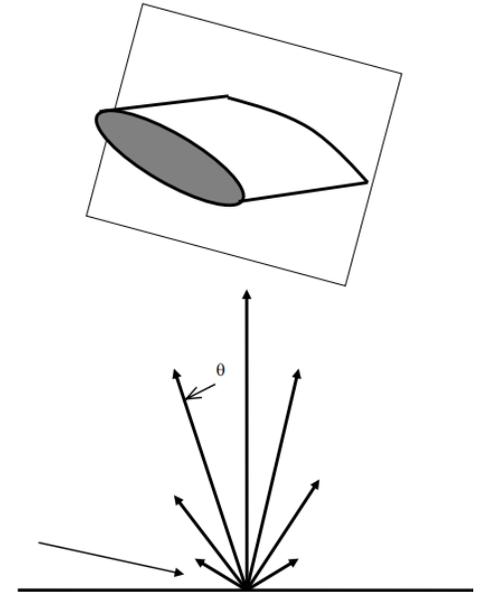
$$C = aC_o$$

1. 도관으로 입사할 확률
 - 관 입구의 면적에 의존

2. 통과해 나갈 확률
 - Diffuse reflection

$$C = aC_o$$

a ; transmission probability
(Clausing coefficient)

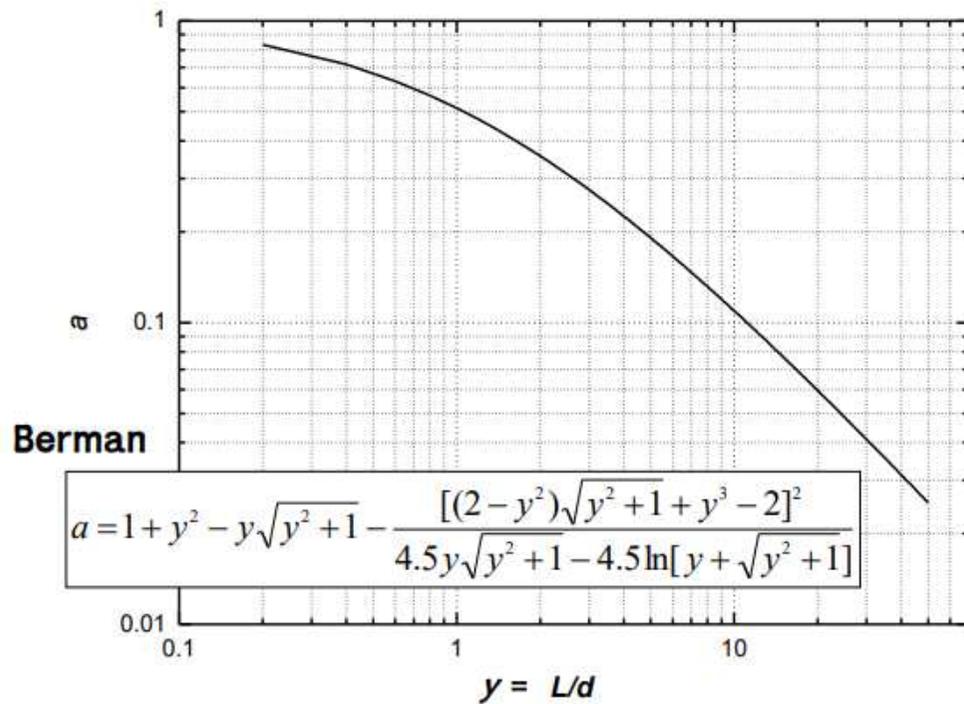


For 20 °C air

$$C = 11.6aA \quad [l/s]$$

Conductance – molecular flow

원형도관의 통과확률



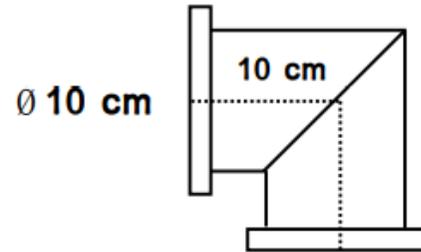
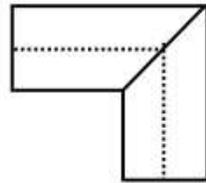
L/d	a	L/d	a	L/d	a	L/d	a
0.1	0.90922	3.7	0.23824	7.4	0.1404	14.6	0.07885
0.2	0.83408	3.8	0.23376	7.6	0.13739	14.8	0.07791
0.3	0.77115	3.9	0.22945	7.8	0.13451	15	0.07699
0.4	0.71779	4	0.2253	8	0.13175	15.2	0.07609
0.5	0.67198	4.1	0.2213	8.2	0.1291	15.4	0.07521
0.6	0.63223	4.2	0.21745	8.4	0.12656	15.6	0.07436
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

Conductance – molecular flow

엘보, 원추형 도관

1. Elbow

$$L_e = L_{\text{중심선}}$$

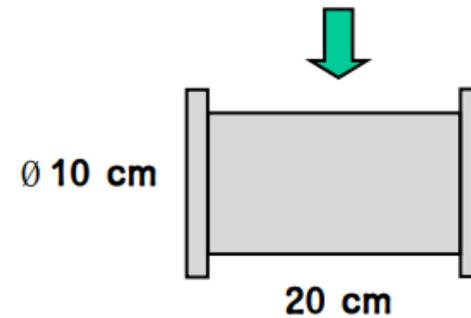
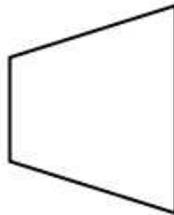


* 20°C, 공기 (cm)

$$\begin{aligned} C &= 11.6aA \\ &= 11.6(0.3561)(3.14 \times 5^2) \\ &= 324.4 \text{ l/s} \end{aligned}$$

2. Cone

$$d_e = \left[\frac{2d_1^2 d_2^2}{d_1 + d_2} \right]^{1/3}$$

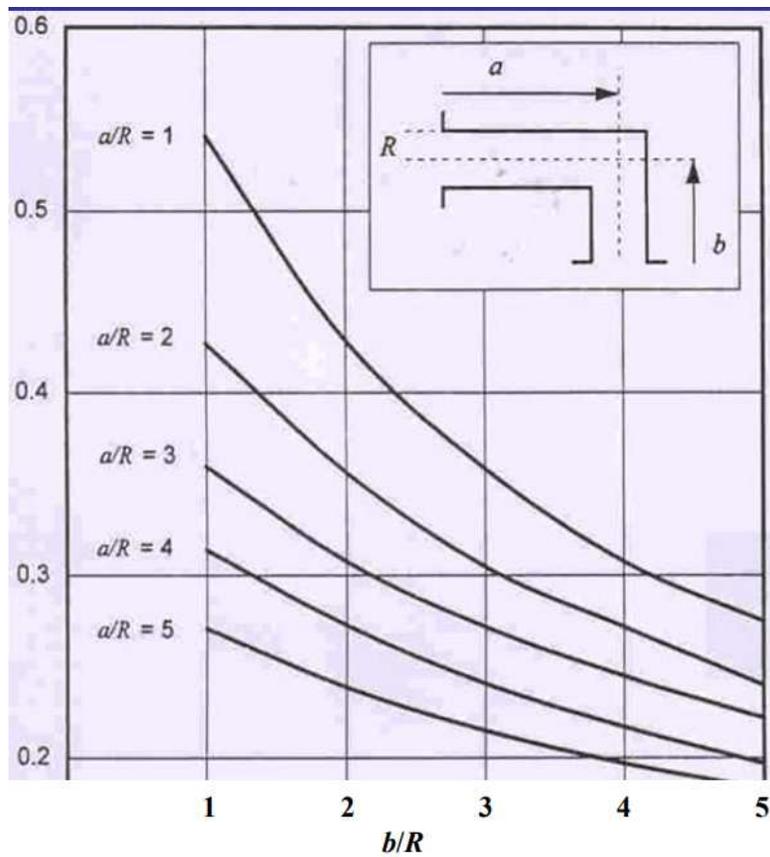


$$\begin{aligned} C &= 11.6(0.35658)(3.14 \times 5^2) \\ &= 324.9 \text{ l/s} \\ &\quad (L/d=2, a=0.35658) \end{aligned}$$

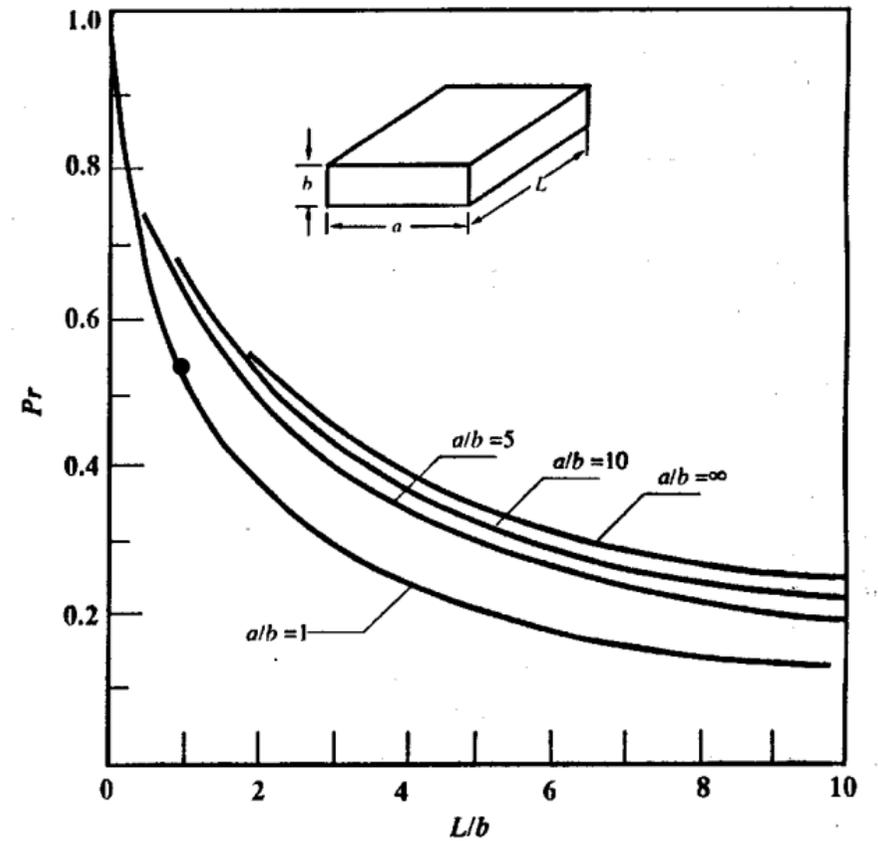
* 오차 ~0.13%

Conductance – molecular flow

Elbow 통과확률

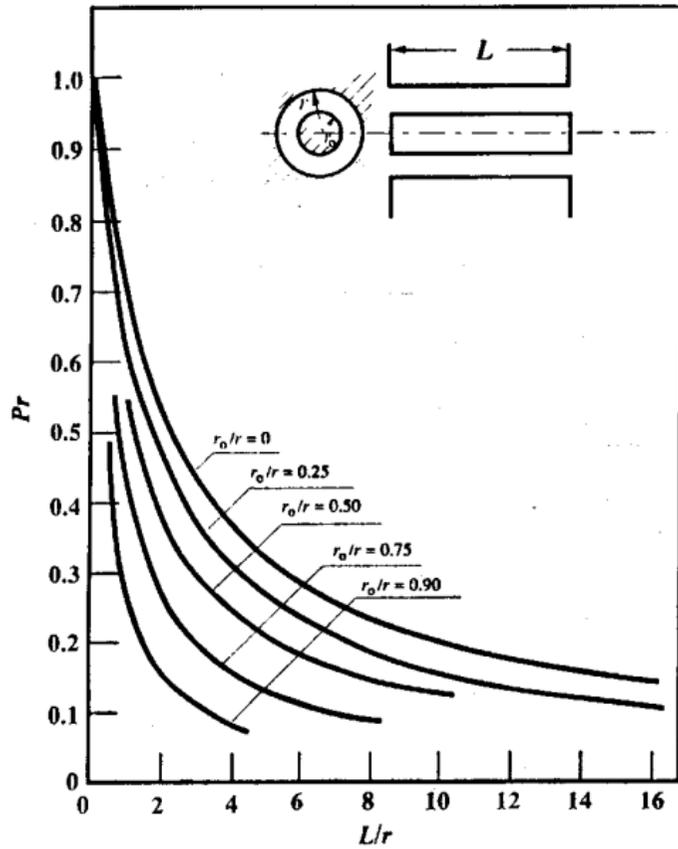


사각도관 통과확률

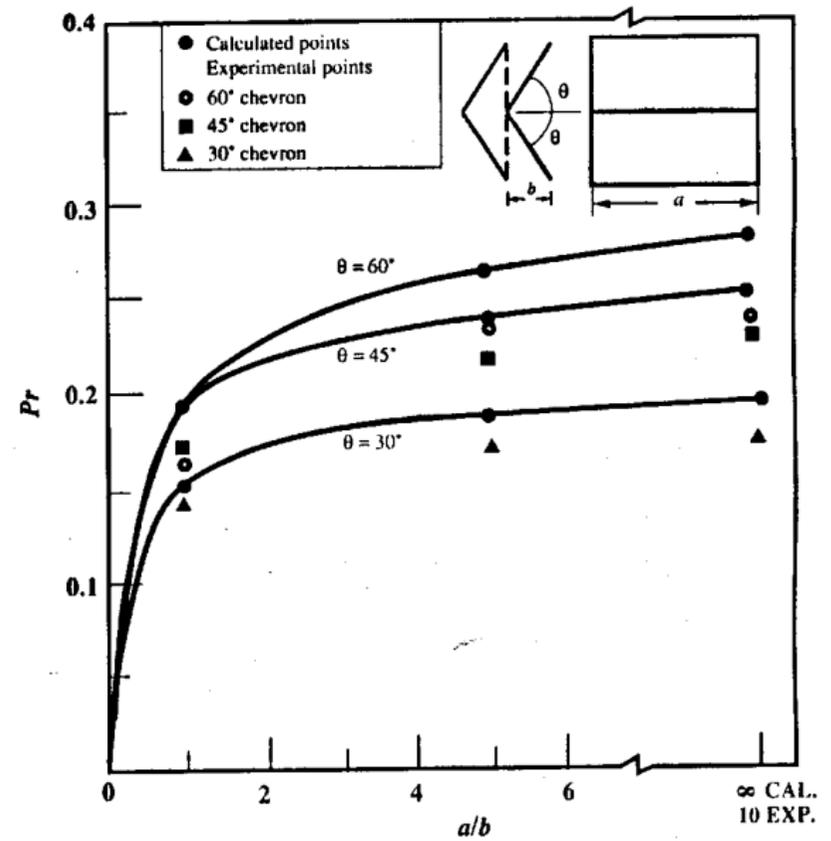


Conductance – molecular flow

이중원통 통과확률



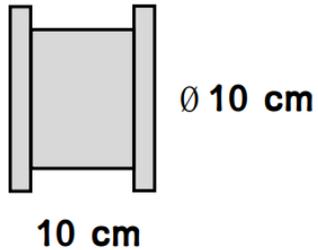
배플 통과확률



Conductance – molecular flow

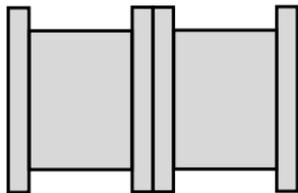
컨덕턴스의 합성

1. 새로운 길이에 대한 클라우징 계수 적용



* 20°C, 공기 (cm)

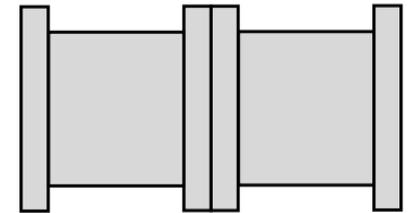
$$C=11.6(0.51423)(3.14 \times 10^2) \\ =468 \text{ l/s} \\ (L/d=1, a=0.51423)$$



$$C=11.6(0.35658)(3.14 \times 10^2) \\ =325 \text{ l/s} \\ (L/d=2, a=0.35658)$$

2. 컨덕턴스 합성 공식 사용

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

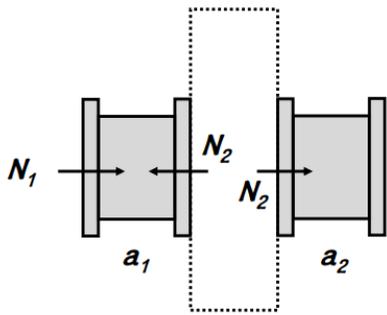


•경계/오차 문제 발생

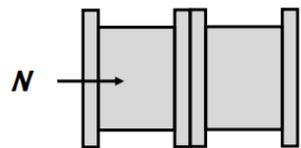
- Entrance effect; directional or random ?
- Beaming effect

Conductance – molecular flow

컨덕턴스의 합성



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



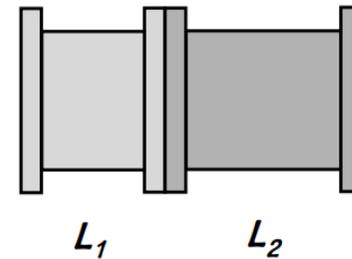
$$a_{\text{clausius}} = 0.35658 \quad (L/d = 2)$$

$$a_{\text{합성}} = 0.25711 \quad (27.9\% \text{오차})$$

동일한 단면에 대해

Oatley

(입구효과는 한번만 고려)



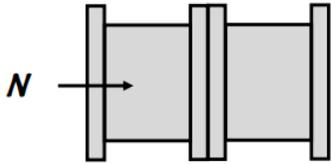
$$C = C_{(L_1+L_2)/d}$$

or

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

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

Conductance – molecular flow



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

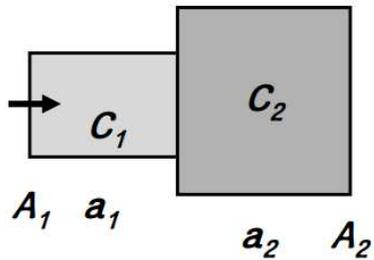
$$a_{\text{합성}} = 0.25711 \quad (27.9\% \text{오차})$$

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

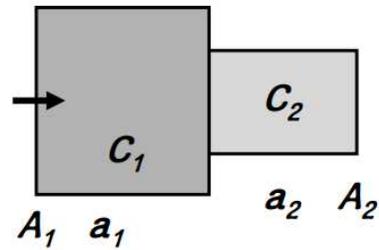
Conductance – molecular flow

동일하지 않은 단면에 대해

작은 관의 입구저항만 고려



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



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

참고문헌

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