제7장 자연대류

7-1 자연대류의 물리적인 메키나즘

부력과 같은 자연 발생적인 수단에 일어나며 자연 대류에서 생긴 유체의 속도는 낮다.

부력 - 유체에 잠긴 물체에 작용하는 상방향의 힘이며 그 크기는 물체에 의해 배제된 유체의 무게

<u>물질의 체적 팽창계수 β</u>

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \qquad (1/k)$$

이상기체의 경우 $\beta = \frac{1}{T}$

자연대류에서 흔히 사용되는 장치는 Mach-Zehmder 간섭계이며 이것은 표면 주위에 있는 유체의 등온선을 나타내준다.

<u>Grashof 수</u>

$$G_r = \frac{\text{부력}}{\text{점성력}} = \frac{g \triangle \rho V}{\rho \nu^2} = \frac{g \beta \triangle T V}{\nu^2}$$

$$= \frac{g\beta(T_s - T_\infty)\delta^3}{\nu^2} \qquad \delta\text{:형상의 특성길이}$$

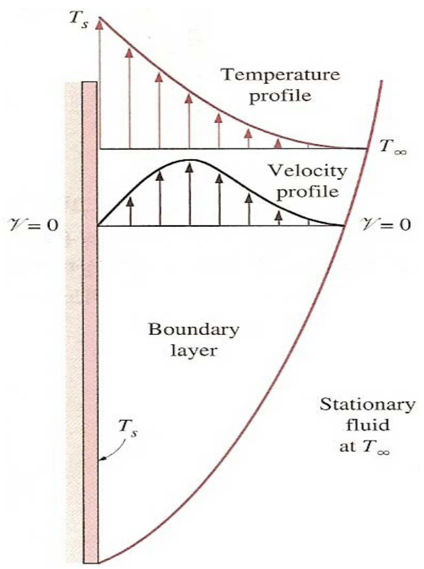
자연대류에서 유동이 층류인지 난류인지 판단

수직판 $G_r < 10^9$ 층류

$G_r > 10^9$ 난류

$\dot{Q}_{conv} = A(T_s - T_\infty)$

7-2 표면위의 자연 대류



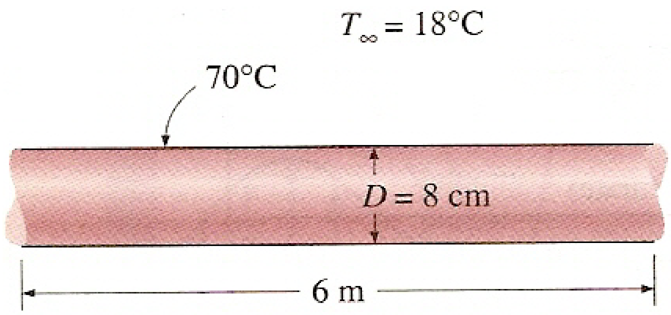
$Ra = Gr \cdot \mathrm{Pr}$

Ra: $Rayleigh$수

$$Nu = \frac{h\delta}{k} = C Ra^n$$

표 7-1에 상세한 식 설명

(ex 7-1)



$T_s = 70℃,\ T_\infty = 18℃$

자연대류에 의한 열손실

(해) $T_f = \frac{T_s + T_\infty}{2}$ 에서 공기의 물성치 (표 A-11)

k=0.0273　　　　Pr=0.710

ν=1.74 x 10^{-5} $\beta = \frac{1}{T_f}$

$$Ra = Gr \cdot \mathrm{Pr} = \frac{g\beta(T_s - T_\infty)\delta^3}{\nu^2}\mathrm{Pr}$$

표 7-1에서 $\delta = D$

$$N_u = \left\{0.6 + \frac{0.387 R_a^{1/6}}{[1+(0.559/P_r)^{8/27}}\right\}^2 = 17.2$$

$$\therefore h = \frac{k}{D} Nu = 5.9w$$

표 4-1

표면위의 자연대류에서 평균 Nusselt 수를 구하는 실험식

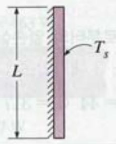
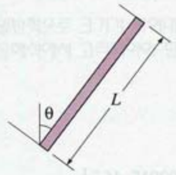
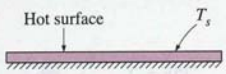
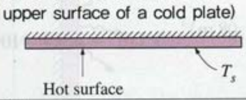
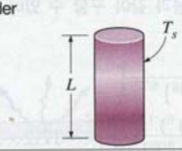
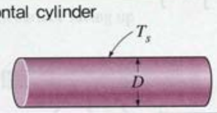
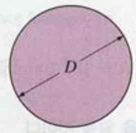
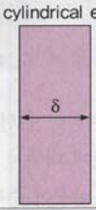
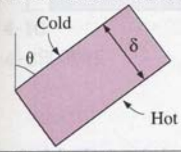
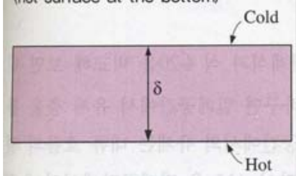
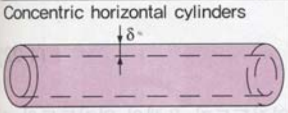
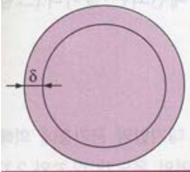
Geometry	Characteristic length (δ)	Range of Ra	Nu	
Vertical plate 	L	$10^4 - 10^9$ $10^9 - 10^{13}$ Entire range	$\text{Nu} = 0.59\text{Ra}^{1/4}$ $\text{Nu} = 0.1\text{Ra}^{1/3}$ $\text{Nu} = \left\{0.825 + \dfrac{0.387\text{Ra}^{1/6}}{[1+(0.492/\text{Pr})^{9/16}]^{8/27}}\right\}^2$ (complex but more accurate)	(4-8) (4-9) (4-10)
inclined plate 	L		Use vertical plate equations as a first degree of approximation Replace g by $g\cos\theta$ for $\text{Ra} < 10^9$	
Horizontal plate (Surface area A and perimeter p) (a) Upper surface of a hot plate (or lower surface of a cold plate) 	A/p	$10^4 - 10^7$ $10^7 - 10^{11}$	$\text{Nu} = 0.54\text{Ra}^{1/4}$ $\text{Nu} = 0.15\text{Ra}^{1/3}$	(4-11) (4-12)
(b) Lower surface of a hot plate (or upper surface of a cold plate) 		$10^5 - 10^{11}$	$\text{Nu} = 0.27\text{Ra}^{1/4}$	(4-13)
Vertical cylinder 	L		A vertical clyinder can be treated as a vertical plate when $D \geq \dfrac{35L}{\text{Gr}^{1/4}}$	(4-14)
Horizontal cylinder 	D	$10^{-5} - 10^{12}$	$\text{Nu} = \left\{0.6 + \dfrac{0.387\text{Ra}^{1/6}}{[1+(0.559/\text{Pr})^{9/16}]^{8/27}}\right\}^2$	(4-15)
Sphere 	$\frac{1}{2}\pi D$	$\text{Ra} \leq 10^{11}$ $(\text{Pr} \geq 0.7)$	$\text{Nu} = 2 + \dfrac{0.589\text{Ra}^{1/4}}{[1+(0.469/\text{Pr})^{9/16}]^{4/9}}$	(4-16)

표 4-2

밀폐공간안의 자연대류에서 평균 Nusselt 수를 구하는 실험 상관식(특성길이 δ는 각각의 도형에 표시된 것과 같다.)

Geometry	Fluid	H/δ	Range of Pr	Range of Ra	Nusselt number	
Vertical rectangular enclosure (or vertical cylindrical enclosure) 	Gas or liquid	–	–	$\mathrm{Ra} < 2000$	$\mathrm{Nu} = 1$	(4-23)
	Gas	11–42	0.5–2	$2\times10^3 - 2\times10^5$	$\mathrm{Nu} = 0.197\,\mathrm{Ra}^{1/4}\left(\frac{H}{\delta}\right)^{-1/9}$	(4-24)
		11–42	0.5–2	$2\times10^5 - 10^7$	$\mathrm{Nu} = 0.073\,\mathrm{Ra}^{1/3}\left(\frac{H}{\delta}\right)^{-1/9}$	(4-25)
	Liquid	10–40	1–20,000	$10^4 - 10^7$	$\mathrm{Nu} = 0.42\,\mathrm{Pr}^{0.012}\,\mathrm{Ra}^{1/4}\left(\frac{H}{\delta}\right)^{-0.3}$	(4-26)
		1–40	1–20	$10^6 - 10^9$	$\mathrm{Nu} = 0.046\,\mathrm{Ra}^{1/3}$	(4-27)
Inclined rectangular enclosure 					Use the correlations for vertical enclosures as a first-degree approximation for $\theta \leq 20^\circ$ by replacing g in the Ra relation by $g\cos\theta$	
Horizontal rectangular enclosure (hot surface at the top)	Gas or liquid	–	–	–	$\mathrm{Nu} = 1$	(4-28)
Horizontal rectangular enclosure (hot surface at the bottom) 	Gas or liquid	–	–	$\mathrm{Ra} < 1700$	$\mathrm{Nu} = 1$	(4-29)
	Gas	–	0.5–2	$1.7\times10^3 - 7\times10^3$	$\mathrm{Nu} = 0.059\,\mathrm{Ra}^{0.4}$	(4-30)
		–	0.5–2	$7\times10^3 - 3.2\times10^5$	$\mathrm{Nu} = 0.212\,\mathrm{Ra}^{1/4}$	(4-31)
		–	0.5–2	$\mathrm{Ra} > 3.2\times10^5$	$\mathrm{Nu} = 0.061\,\mathrm{Ra}^{1/3}$	(4-32)
	Liquid	–	1–5000	$1.7\times10^3 - 6\times10^3$	$\mathrm{Nu} = 0.012\,\mathrm{Ra}^{0.6}$	(4-33)
		–	1–5000	$6\times10^3 - 3.7\times10^4$	$\mathrm{Nu} = 0.375\,\mathrm{Ra}^{0.2}$	(4-34)
		–	1–20	$3.7\times10^4 - 10^8$	$\mathrm{Nu} = 0.13\,\mathrm{Ra}^{0.3}$	(4-35)
		–	1–20	$\mathrm{Ra} > 10^8$	$\mathrm{Nu} = 0.057\,\mathrm{Ra}^{1/3}$	(4-36)
Concentric horizontal cylinders 	Gas or liquid	–	1–5000	$6.3\times10^3 - 10^6$	$\mathrm{Nu} = 0.11\,\mathrm{Ra}^{0.29}$	(4-37)
			1–5000	$10^6 - 10^8$	$\mathrm{Nu} = 0.40\,\mathrm{Ra}^{0.20}$	(4-38)
Concentric spheres 	Gas or liquid	–	0.7–4000	$10^2 - 10^9$	$\mathrm{Nu} = 0.228\,\mathrm{Ra}^{0.226}$	(4-39)

7-3 밀폐공간 안에서의 자연대류

뜨거운 판이 위에 있는 경우는 자연 대류는 발생하지 않는다. 그 외의 경우는 자연 대류가 발생한다.

$Q = hA(T_1 - T_2)$

h는 Nu 로 구해지는데 $Nu = \frac{h\delta}{k}$ 로 표 7-2에 설명되어 있다.

여기서 단면적 A 는

A = HL 사각 밀폐공간

$\frac{\pi L(D_2 - D_1)}{\ln(D_2/D_1)}$ 동심원통

$\pi D_1 D_2$ 동심구

ex 7-3) 이중 유리창을 통한 열전달

H = 0.8m, δ = 0.02, $T_1 = 12℃$, $T_2 = 2℃$ L=2m

(go) $T_{ave} = \frac{T_1 + T_2}{2}$ 에서 표 A-11에서 공기의 물성치

$k, \Pr, \nu, \beta$계산

$Ra = Gr \cdot \Pr = \frac{g\beta(T_1 - T_2)\delta^3}{\nu^2}\Pr$

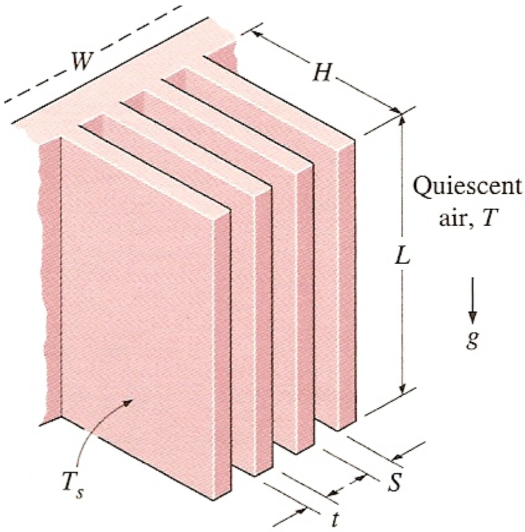
표7-2의 식 7-23에서

$Nu = 0.197Ra^{1/4}(\frac{H}{\delta})^{-1.9}$

사각 밀폐공간이므로 A=HL

$Q = hA(T_1 - T_2) = kNu \cdot A\frac{T_1 - T_2}{\delta} = 25.9\,W$

7-4 휜이 달린 표면에서 자연 대류



최적의 휜 간격

$$S_{opt} = 2.714\frac{L}{R^{1/4}}$$

최적 휜 간격시 열전달계수

$$h = 1.31k/S_{opt}$$

7-5 자연 강제 복합 대류

$G_r / R_e^2 < 0.1$ 자연대류무시

$G_r / R_e^2 > 10$ 강제대류무시