PERPINDAHAN PANAS KONVEKSI PAKSA (HUBUNGAN EMPIRIS DAN PRAKTIS)

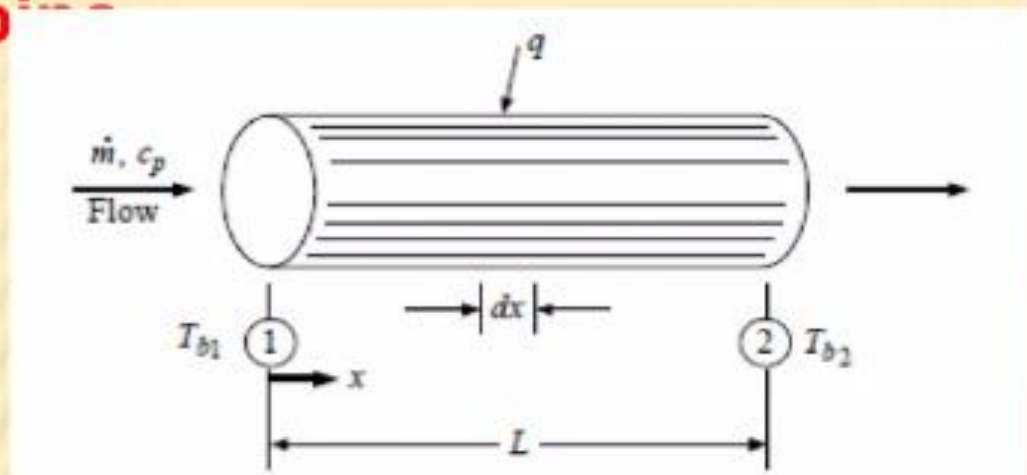
- Pendekatan Perhitungan PP konveksi paksa: analisa bilangan tanpa dimensi (N_{re}, N_{Pt})
- Bil. Tanpa dimensi:
  - diturunkan dari analitik
  - dapat dikorelasikan dengan eksperimen

Perhitungan analitik: mengaplikasikan semua penalaran besaran fisika-→ sulit di aplikasikan

Jalan keluar: bilangan tanpa dimensi

KONVEKSI PAKSA

Hubungan Empiris pada aliran tabung dan p



Bagaimana menentukan h: Apakah h = atau ≠T(r,θ,z)

$$q = \dot{m} c_p (T_{b_2} - T_{b_1})$$

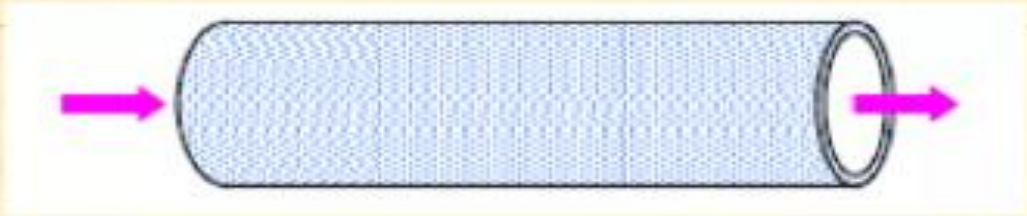
PP karena perbedaan suhu :

PP da

$$dq = \dot{m} c_p dT_b = h(2\pi r)dx(T_w - T_b)$$

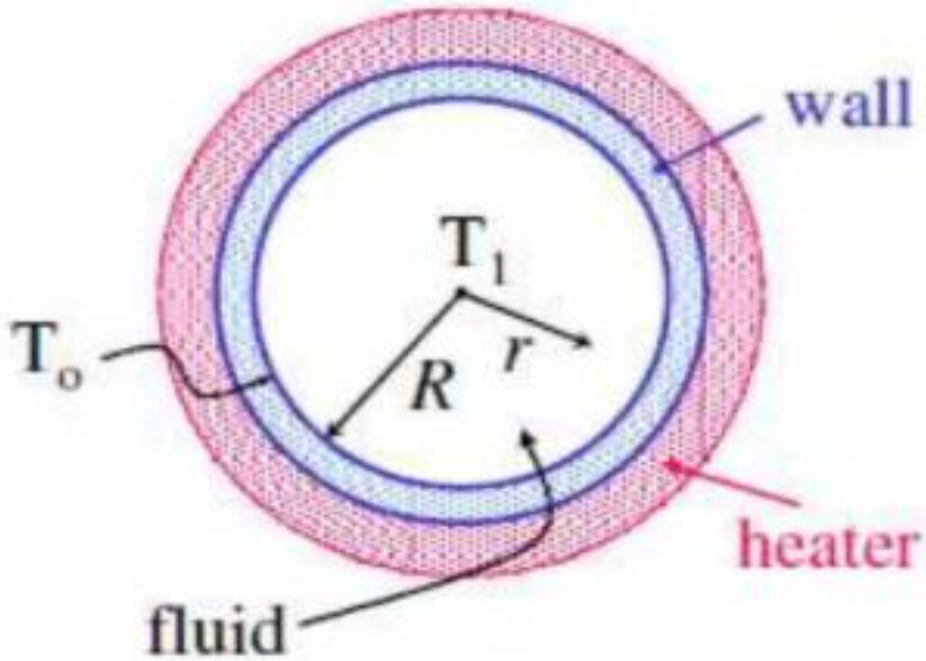
$$q = hA(T_w - T_b)_{av}$$

KONVEKSI PAKSA

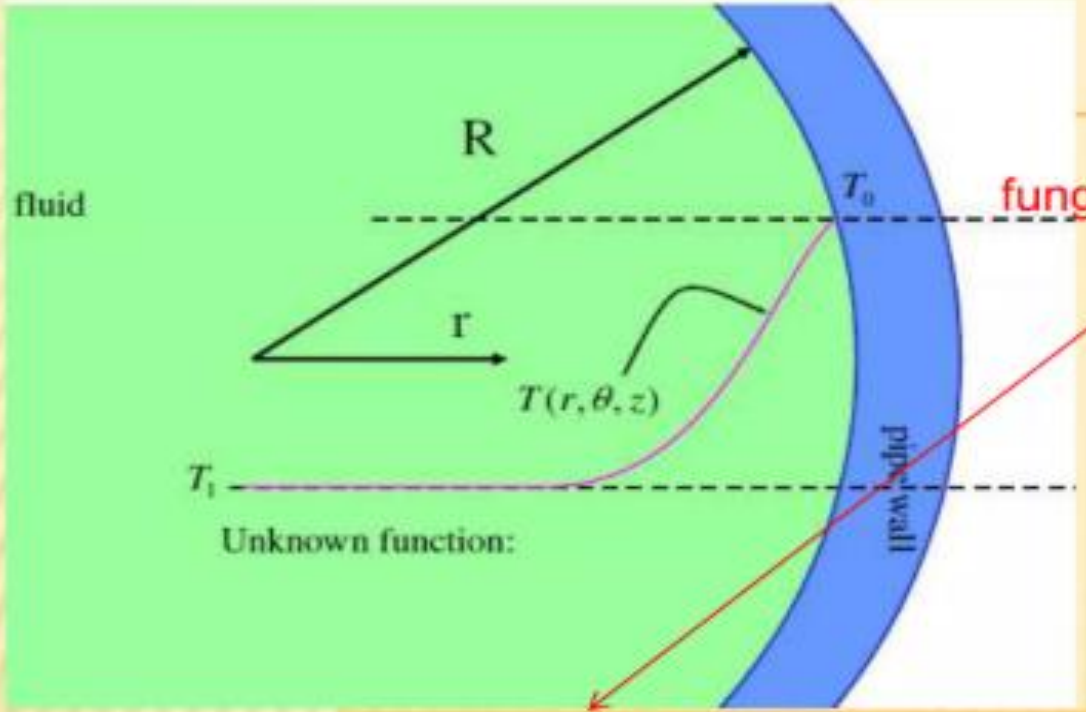


$T_o > T_1$

$\frac{q_r}{A} < 0$



KONVEKSI PAKSA



fungsif θ, *z*

Total panas pada dinding (konveksi)

$$\int_0^{2\pi}\int_0^{L} -k\left.\frac{\partial T}{\partial r}\right|_{r=R} R\,dz\,d\theta = q_r = h(2\pi RL)(T_1 - T_o)$$

Total Panas konduski ke dinding dari fluida

KONVEKSI PAKSA

Bilangan tanpa dimensi yang dapat dibuat

position:

$$r^* \equiv \frac{r}{D}$$

$$z^* \equiv \frac{z}{D}$$

temperature:

$$T^* \equiv \frac{T - T_o}{(T_1 - T_o)}$$

$$h(\pi DL)(T_1 - T_o) = \int_0^{2\pi} \int_0^{L/D} -k \left.\frac{\partial T^*}{\partial r^*}\right|_{r^*=1/2} \frac{(T_1 - T_o)}{D} \frac{D^2}{2} dz^* d\theta$$

$$2\pi \underbrace{\left(\frac{hD}{k}\right)}_{\text{Nusselt number, Nu}} \left(\frac{L}{D}\right) = \int_0^{2\pi} \int_0^{L/D} -\left.\frac{\partial T^*}{\partial r^*}\right|_{r^*=1/2} dz^* d\theta$$

Nusselt number, Nu
(dimensionless heat-transfer coefficient)

$$Nu = Nu\left(T^*, \frac{L}{D}\right)$$

one additional dimensionless group

KONVEKSI PA

Show all slides | Show most read first

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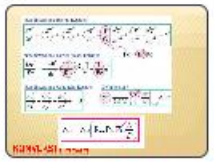

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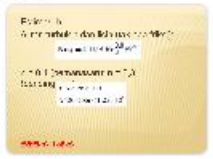

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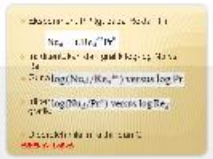
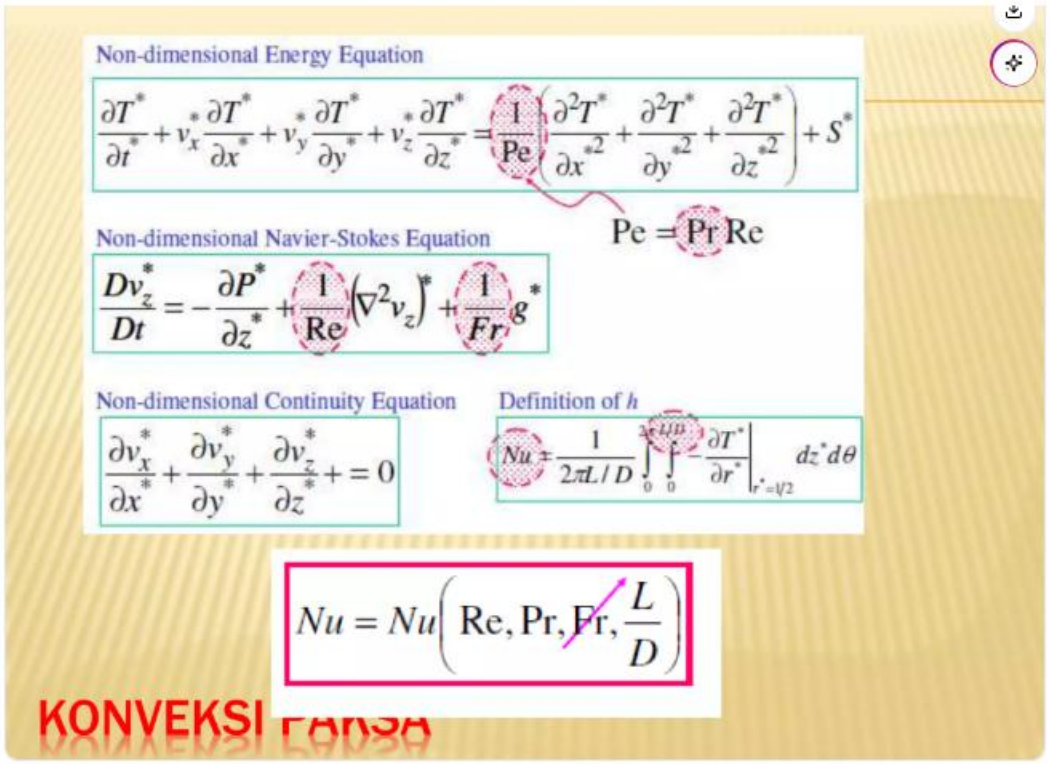




Estimasi h:

Aliran turbulen dan licin (tak ada friksi):

$$\mathrm{Nu}_d = 0.023\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^n$$

n = 0,4 (pemanasan); n = 0,3 (pendingi[illegible])

$$0.6 < \mathrm{Pr} < 100$$

$$2500 < \mathrm{Re} < 1.25 \times 10^5$$

- Untuk aliran turbulen dan pada tabung licin:

$$\mathrm{Nu} = 0.0214(\mathrm{Re}^{0.8} - 100)\mathrm{Pr}^{0.4}$$

for $0.5 < \mathrm{Pr} < 1.5$ and $10^4 < \mathrm{Re} < 5 \times 10^6$ or

$$\mathrm{Nu} = 0.012(\mathrm{Re}^{0.87} - 280)\mathrm{Pr}^{0.4}$$

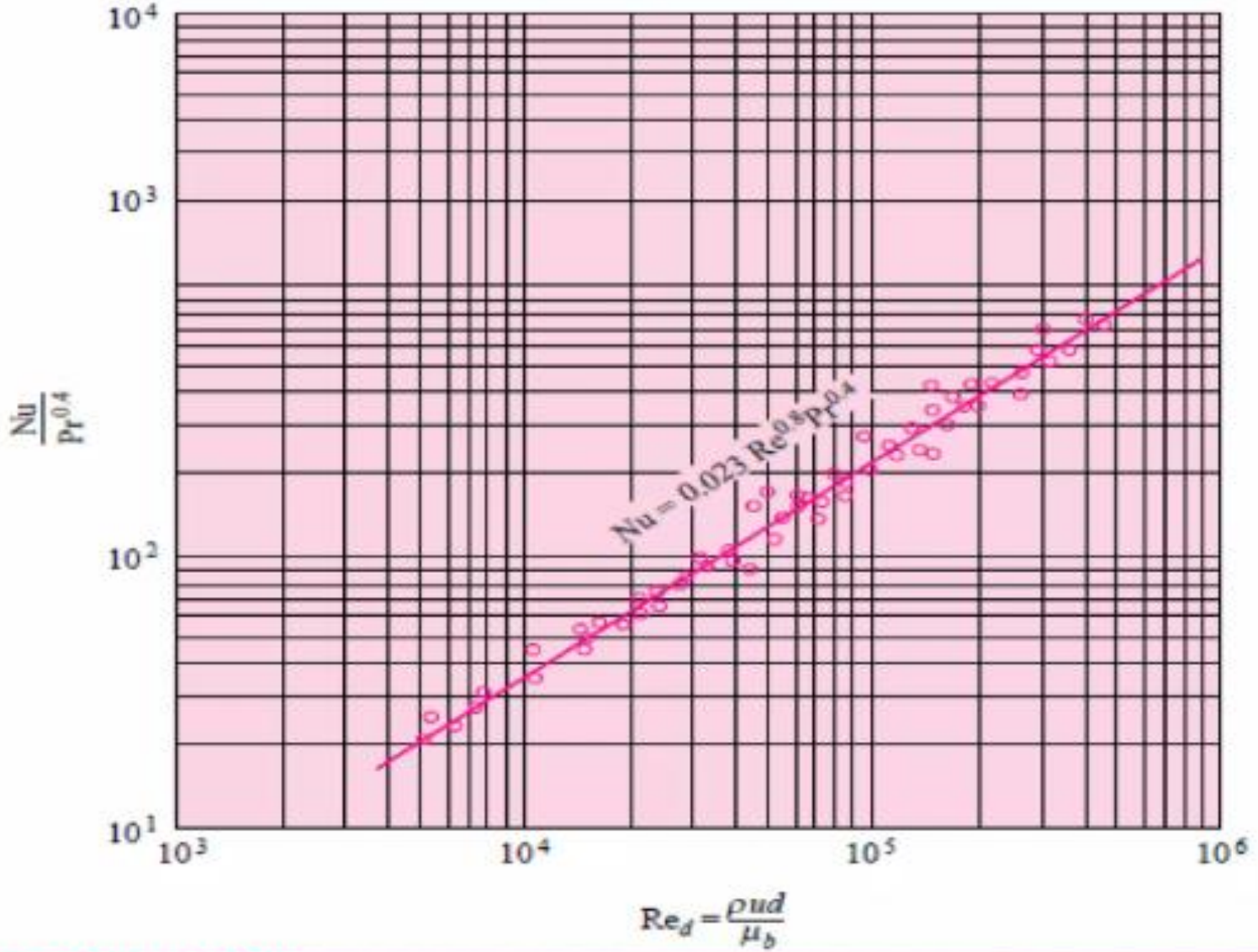
for $1.5 < \mathrm{Pr} < 500$ and $3000 < \mathrm{Re} < 10^6$.

- Eksperimen: PP tgt pada Re dan Pr

$$Nu_d = C Re_d^{\,m} Pr^n$$

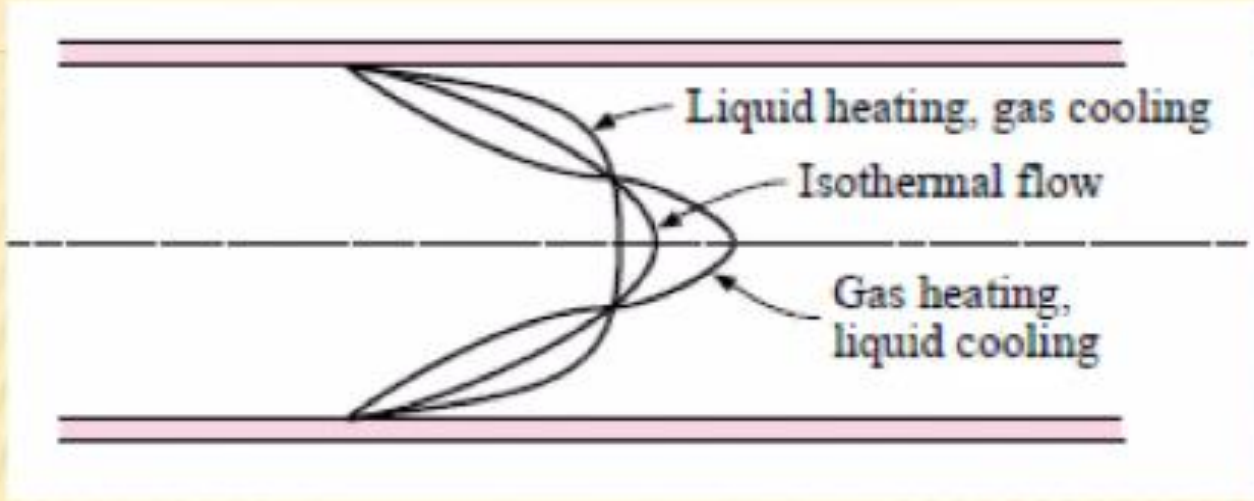
- m: ditentukan dari grafik log-log Nu vs Re
- Guna $\log(Nu_d / Re_d^{\,m})$ versus $\log Pr$
- diper $\log(Nu_d / Pr^n)$ versus $\log Re_d$ grafik:
- Diperoleh nilai m akhir dan C

Figure 6-2 | Typical data correlation for forced convection in smooth tubes, turbulent flow.



KONVEKSI PAKSA

- Pengaruh suhu



$$\mu_b > \mu_w$$

$$\mathrm{Nu}_d = 0.027\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

- Gunakan data suhu bulk, kecuali μ_w = suhu dinding

KONVEKSI PAKSA

- Untuk aliran belum berkembang (pintu masuk tabung):

$$\mathrm{Nu}_d = 0.036\,\mathrm{Re}_d^{0.8}\mathrm{Pr}^{1/3}\left(\frac{d}{L}\right)^{0.055} \qquad \text{for } 10 < \frac{L}{d} < 400$$

- Persamaan yg lebih akurat untuk aliran turbulen dan licin pada tabung:

$$\mathrm{Nu}_d = \frac{(f/8)\,\mathrm{Re}_d\mathrm{Pr}}{1.07 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3} - 1)}\left(\frac{\mu_b}{\mu_w}\right)^n$$

$n = 0.11$ for $T_w > T_b$, $n = 0.25$ for $T_w < T_b$, and $n = 0$

- Tabung licin: $f = (1.82\ \log_{10}\mathrm{Re}_d - 1.64)^{-2}$
- Semua sifat ditentukan pada suhu:

$$T_f = (T_w + T_b)/2$$

KONVEKSI PAKSA

- Ketentuan: pers berlaku:

$0.5 < \mathrm{Pr} < 200$	for 6 percent accuracy
$0.5 < \mathrm{Pr} < 2000$	for 10 percent accuracy
$10^4 < \mathrm{Re}_d < 5 \times 10^6$	
$0.8 < \mu_b/\mu_w < 40$	

- Aliran laminar dan berkembang penuh:

$$\overline{\mathrm{Nu}}_d = 3.66 + \frac{0.0668(d/L)\,\mathrm{Re}_d\mathrm{Pr}}{1 + 0.04[(d/L)\,\mathrm{Re}_d\mathrm{Pr}]^{2/3}}$$

- Rumus lebih sederhana PP dlm aliran laminar dalam tabung (Sieder and Tate)

$$\overline{\mathrm{Nu}}_d = 1.86(\mathrm{Re}_d \mathrm{Pr})^{1/3} \left(\frac{d}{L}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

- Syarat: $\mathrm{Re}_d \mathrm{Pr} \frac{d}{L} > 10$, sifat fluida pada suhu bulk

Fluida melalui pita/tabung Kasar

Tinjau kembali: fluida melalui pipa/tabung licin

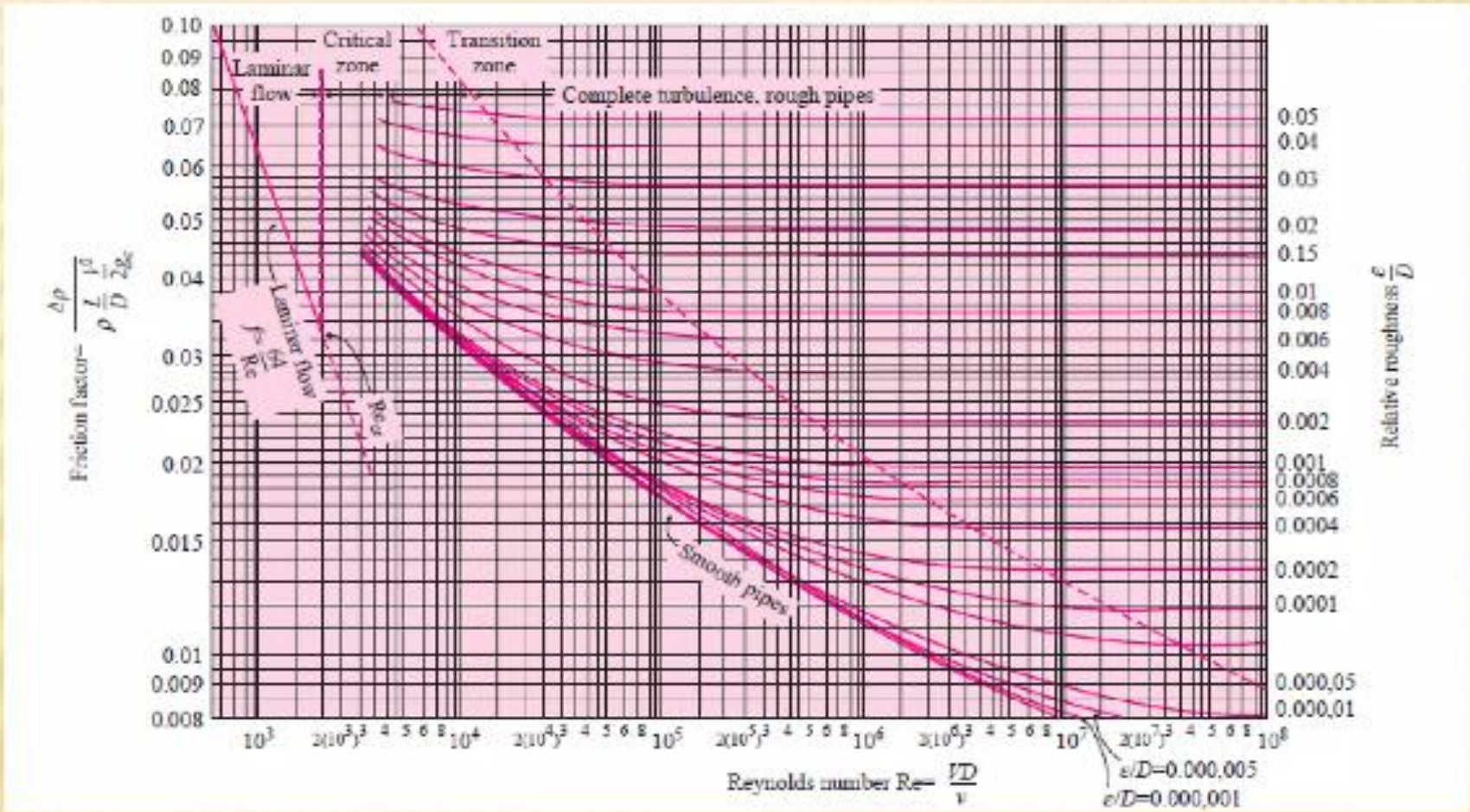
$$\mathrm{Nu}_d = \frac{(f/8)\,\mathrm{Re}_d \mathrm{Pr}}{1.07 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3} - 1)} \left(\frac{\mu_b}{\mu_w}\right)^n$$

Tabung/pipa kasar (ε/D > 0): koef frikdi ditentukan dengan:

a. St = bilangan Stanton $\mathrm{St}_b\,\mathrm{Pr}_f^{2/3} = \frac{f}{8}$ $\mathrm{St} = \frac{h}{\rho c_p u}$

b. $\Delta p = f\frac{L}{d}\rho\frac{u_m{}^2}{2g_c}$ μ_m = kec. Rata-rata

KONVEKSI PAKSA



KONVEKSI PAKSA

c. Menggunakan rumus:

$$f = 1.325 / \left[\ln(\varepsilon/3.7d) + 5.74/\mathrm{Re}_d^{0.9}\right]^2$$ untuk:

$$10^{-6} < \varepsilon/d < 10^{-3} \text{ and } 5000 < \mathrm{Re}_d < 10^8$$

Saluran bentuk lingkaran: gunakan diamater D

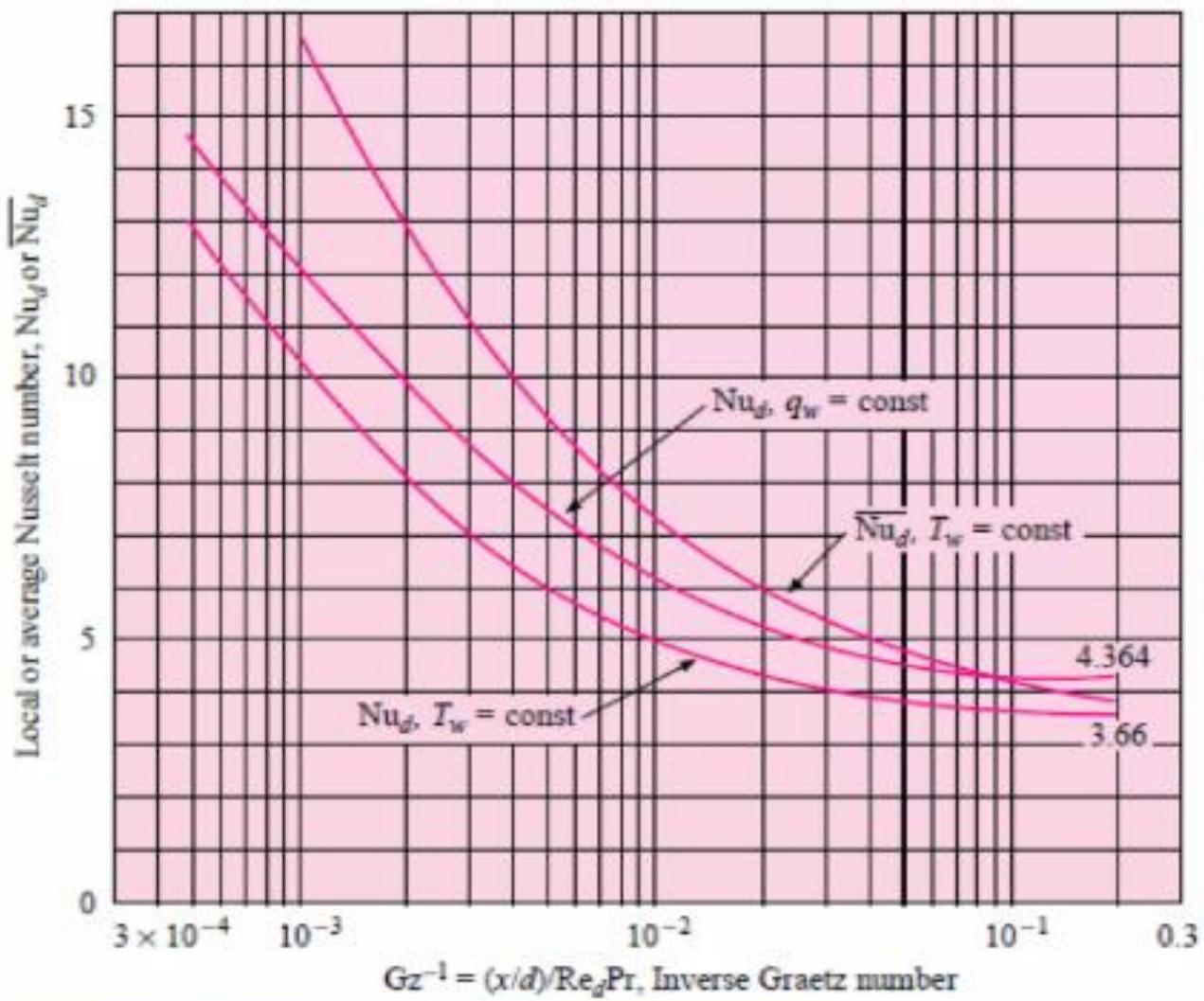
Saluran tak beraturan: gunakan dimater hidrauli $D_H = \frac{4A}{P}$

Luas Permukaan

Perimeter Basah

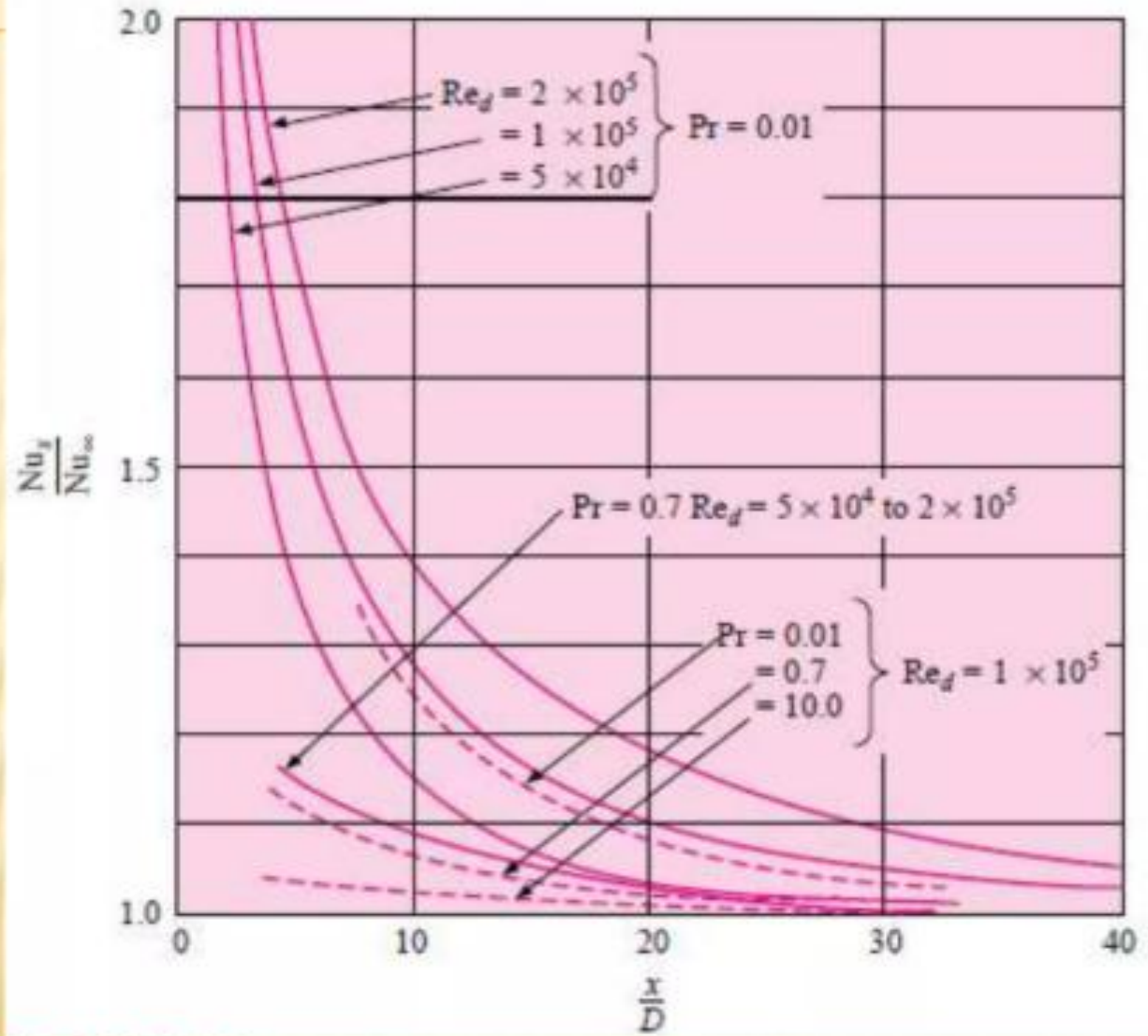
Bil Nu pada pintu masuk aliran laminer pada tabung $\text{Graetz number} = \mathrm{Gz} = \mathrm{Re}\,\mathrm{Pr}\frac{d}{x}$ versi Bil. Graetz:

Figure 6-5 | Local and average Nusselt numbers for circular tube thermal entrance regions in fully developed laminar flow.



KONVEKSI PAKSA

Figure 6-6 | Turbulent thermal entry Nusselt numbers for circular tubes with q_w = constant.



KONVEKSI PAKSA

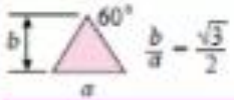
- Gesekan fluida dan PP pada berbagai bentuk penampang saluran:
- Istilah:

Nu*H* = Bil. Nusselt rata-rata untuk fluks kalor seragam dalam arah aliran, dan suhu dinding seragam pada penempang aliran tertentu

Nu*T* = Bil Nusselt rata-rata untuk fluks kalor seragam pada arah maupun sekeliling saluran

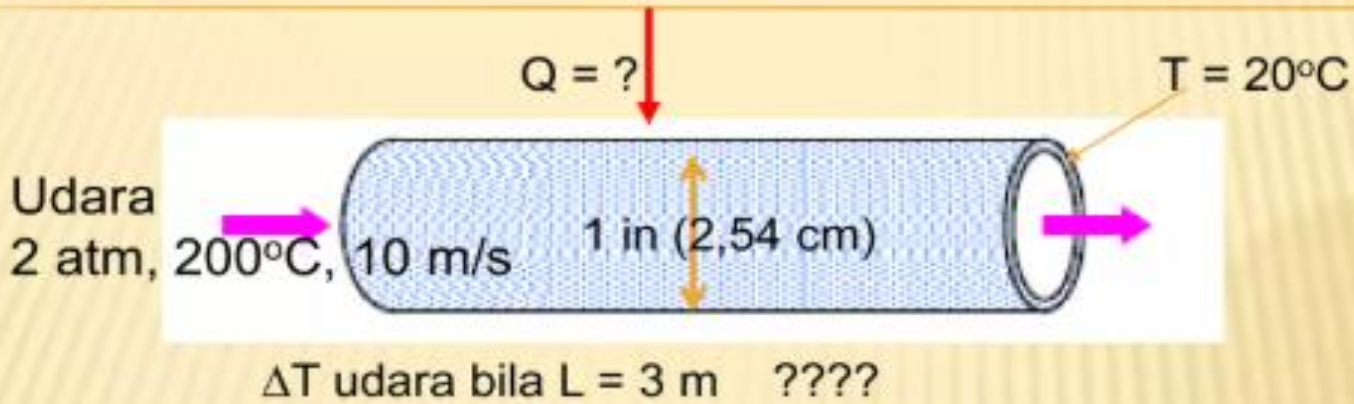
*f*Re*DH* /4 = perkalian faktor friksi dan bil. Reynold pada diameter hidrolik

Table 6-1 | Heat transfer and fluid friction for fully developed laminar flow in ducts of various cross sections. Average Nusselt numbers based on hydraulic diameters of cross sections.

Geometry ($L/D_h > 100$)	Nu_H Constant axial wall heat flux	Nu_T Constant axial wall temperature	$f\,Re_{D_H}/4$
 $\frac{b}{a} = \frac{\sqrt{3}}{2}$	3.111	2.47	13.333
 $\frac{b}{a} = 1$	3.608	2.976	14.227
	4.002	3.34	15.054
 $\frac{b}{a} = \frac{1}{2}$	4.123	3.391	15.548
	4.364	3.657	16.000
 $\frac{b}{a} = \frac{1}{4}$	5.331	4.44	18.23
 $\frac{b}{a} = \frac{1}{3}$	4.79	3.96	17.25
 $\frac{b}{a} = \frac{1}{8}$	6.490	5.597	20.585
$\frac{b}{a} = 0$	8.235	7.541	24.000
 $\frac{b}{a} = 0$	5.385	4.861	24.000

KONVEKSI PAKSA

- Contoh Soal:



- Penyel.:
- Re → laminer atau turbulen ?? → pilih rumus empiris

- Suhu bulk : 200°C

$$\rho = \frac{p}{RT} = \frac{(2)(1.0132 \times 10^5)}{(287)(473)} = 1.493 \text{ kg/m}^3 \qquad [0.0932 \text{ lb}_m/\text{ft}^3]$$

$$\text{Pr} = 0.681$$

$$\mu = 2.57 \times 10^{-5} \text{ kg/m} \cdot \text{s} \qquad [0.0622 \text{ lb}_m/\text{h} \cdot \text{ft}]$$

$$k = 0.0386 \text{ W/m} \cdot {}^\circ\text{C} \qquad [0.0223 \text{ Btu/h} \cdot \text{ft} \cdot {}^\circ\text{F}]$$

$$c_p = 1.025 \text{ kJ/kg} \cdot {}^\circ\text{C}$$

$$\text{Re}_d = \frac{\rho u_m d}{\mu} = \frac{(1.493)(10)(0.0254)}{2.57 \times 10^{-5}} = 14,756$$

- Aliran turbulen, gunakan rumus:

$$\text{Nu}_d = \frac{hd}{k} = 0.023 \text{ Re}_d^{0.8} \text{ Pr}^{0.4} = (0.023)(14,756)^{0.8}(0.681)^{0.4} = 42.67$$

$$h = \frac{k}{d}\text{Nu}_d = \frac{(0.0386)(42.67)}{0.0254} = 64.85 \text{ W/m}^2 \cdot {}^\circ\text{C} \qquad [11.42 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}]$$

KONVEKSI PAKSA

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KONVEKSI PAKSA

PP/satuan panjang:

$$\frac{q}{L} = h\pi d(T_w - T_b) = (64.85)\pi(0.0254)(20) = 103.5 \text{ W/m} \qquad [107.7 \text{ Btu/ft}]$$

Bila L = 3 m: $q = \dot{m} c_p \Delta T_b = L\left(\frac{q}{L}\right)$

$$\dot{m} = \rho u_m \frac{\pi d^2}{4} = (1.493)(10)\pi \frac{(0.0254)^2}{4}$$

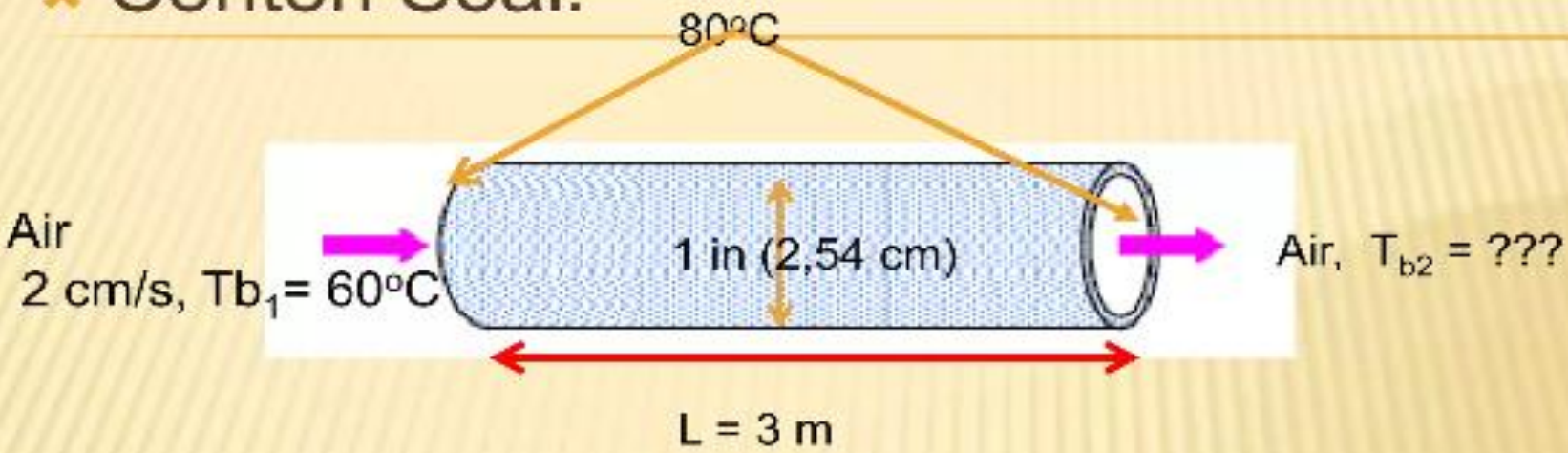
$$= 7.565 \times 10^{-3} \text{ kg/s} \qquad [0.0167 \text{ lb}_m/\text{s}]$$

$$(7.565 \times 10^{-3})(1025)\Delta T_b = (3.0)(103.5)$$

$$\Delta T_b = 40.04^\circ\text{C} \qquad [104.07^\circ\text{F}]$$

Konveksi Paksa

- Contoh Soal:



- Penyelesaian:
- Re fluida (60°C) → lam. Atau turb. ??

- Sifat air 60°C (suhu ketika masuk) :

$$\rho = 985\ \text{kg/m}^3 \qquad c_p = 4.18\ \text{kJ/kg}\cdot^\circ\text{C}$$
$$\mu = 4.71 \times 10^{-4}\ \text{kg/m}\cdot\text{s} \qquad [1.139\ \text{lb}_m/\text{h}\cdot\text{ft}]$$
$$k = 0.651\ \text{W/m}\cdot^\circ\text{C} \qquad \text{Pr} = 3.02$$

- $\text{Re}_d = \dfrac{\rho u_m d}{\mu} = \dfrac{(985)(0.02)(0.0254)}{4.71 \times 10^{-4}} = 1062$ (laminer)
- Parameter tambahan untuk aliran laminer:

$$\text{Re}_d \text{Pr} \frac{d}{L} = \frac{(1062)(3.02)(0.0254)}{3} = 27.15 > 10$$

Pada T ???

$$\overline{\text{Nu}}_d = 1.86(\text{Re}_d \text{Pr})^{1/3} \left(\frac{d}{L}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

KONVEKSI PAKSA

- Tentukan suhu rata-rata fluida→ sifat fluida

$T = (T_{b2}-T_{b1})/2$; $T_w = 80^oC$ - $\mu_w = 3.55 \times 10^{-4}\ \mathrm{kg/m \cdot s}$

- Neraca Energi:

$$q = h\pi dL\left(T_w - \frac{T_{b_1}+T_{b_2}}{2}\right) = \dot{m}c_p(T_{b_2}-T_{b_1})$$

- Kaedah trial and error: $T_{b2(tebakan)}$ → h_{hit} → neraca energi → $T_{b2\ (hit)}$ bila $|T_{b2(tebakan)} - T_{b2\ (hit)}| = kecil$, maka $T_{b2(tebakan)}$ diterima

KONVEKSI PAKSA

- Ambil $T_{b2tebakan}$ = 60°C, maka

$$\mathrm{Nu}_d = (1.86)\left[\frac{(1062)(3.02)(0.0254)}{3}\right]^{1/3}\left(\frac{4.71}{3.55}\right)^{0.14} = 5.816$$

$$h = \frac{k\mathrm{Nu}_d}{d} = \frac{(0.651)(5.816)}{0.0254} = 149.1\ \mathrm{W/m^2 \cdot °C} \qquad [26.26\ \mathrm{Btu/h \cdot ft^2 \cdot °F}]$$

- $$\dot{m} = \rho\frac{\pi d^2}{4}u_m = \frac{(985)\pi(0.0254)^2(0.02)}{4} = 9.982 \times 10^{-3}\ \mathrm{kg/s}$$

- T_{b2} = ?? Dari NE

$$(149.1)\pi(0.0254)(3.0)\left(80 - \frac{T_{b_2} + 60}{2}\right) = (9.982 \times 10^{-3})(4180)(T_{b_2} - 60)$$

KONVEKSI PAKSA

- $T_{b2\ hitung}$ = 71,98°C → gunakan untuk menghitung T rata-rata fluida → sifat-sifat fluida
- T_b rata-rata = (71,98+60)/2 = 66°C
- Diperoleh sifat-sifat air:

$$\rho = 982\ \text{kg/m}^3 \qquad c_p = 4185\ \text{J/kg} \cdot ^\circ\text{C} \qquad \mu = 4.36 \times 10^{-4}\ \text{kg/m} \cdot \text{s}$$
$$k = 0.656\ \text{W/m} \cdot ^\circ\text{C} \qquad \text{Pr} = 2.78$$

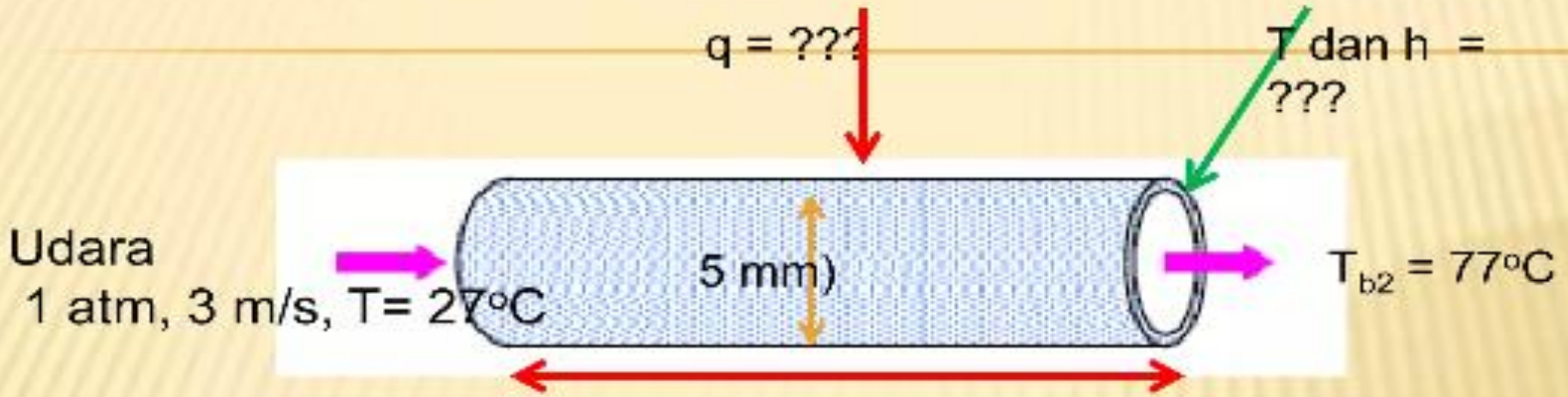
$$\text{Re}_d = \frac{(1062)(4.71)}{4.36} = 1147 \qquad \text{Re Pr}\frac{d}{L} = \frac{(1147)(2.78)(0.0254)}{3} = 27.00$$

$$\text{Nu}_d = (1.86)(27.00)^{1/3}\left(\frac{4.36}{3.55}\right)^{0.14} = 5.743$$

$$h = \frac{(0.656)(5.743)}{0.0254} = 148.3\ \text{W/m}^2 \cdot ^\circ\text{C}$$

KONVEKSI PAKSA

- Masukkan h ke NE untuk memperoleh nilai $T_{b2\ hit\ baru}$
- Diperoleh : $T_{b_2} = 71.88°C \qquad [161.4°F]$
- Dapat diterima karena perbedaan kecil



- Penyelesaian: L = 10 cm
- Fluida (Udara), T_b rata-rata = (27+77)/2 = 5

$$\nu = 18.22 \times 10^{-6}\ \text{m}^2/\text{s} \qquad \text{Pr} = 0.703 \qquad k = 0.02814\ \text{W/m} \cdot °\text{C}$$

$$\text{Re}_d = \frac{ud}{\nu} = \frac{(3)(0.005)}{18.22 \times 10^{-6}} = 823$$

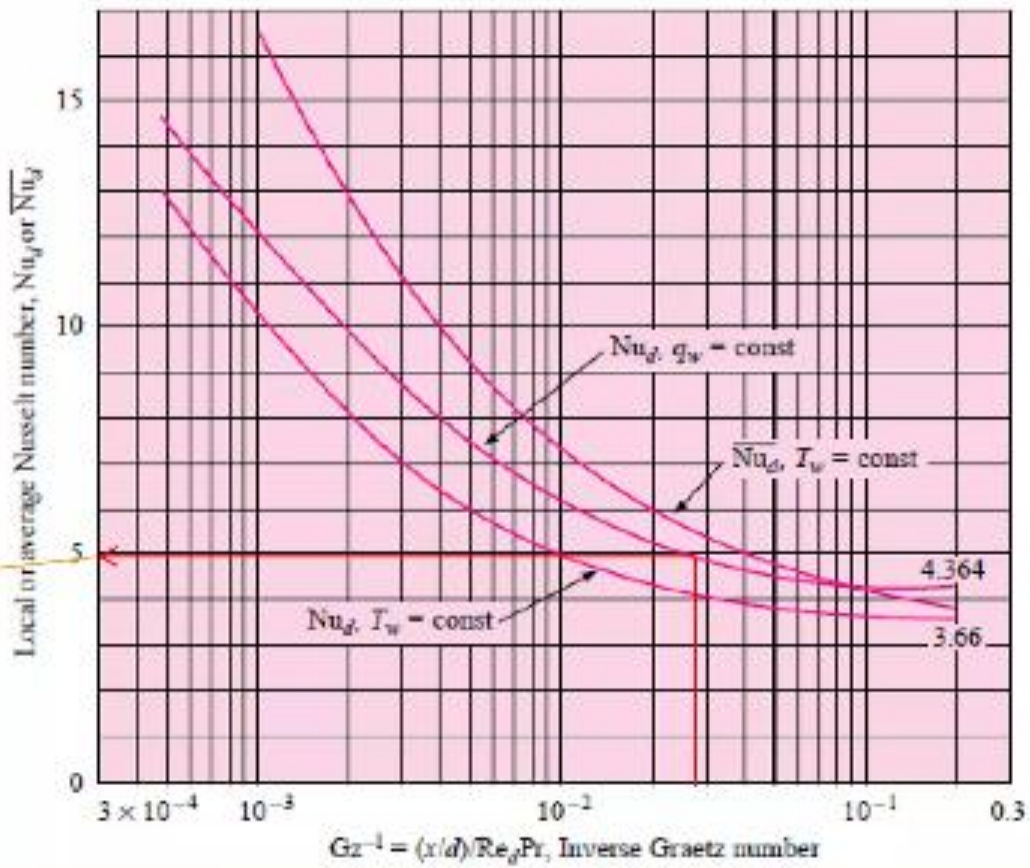
→ Aliran Laminer

KONVEKSI PAKSA

- Tabung cukup pendek,

$$Gz^{-1} = \frac{1}{Re_d Pr}\frac{x}{d} = \frac{0.1}{(823)(0.703)(0.005)} = 0.0346$$

Figure 6-5 | Local and average Nusselt numbers for circular tube thermal entrance regions in fully developed laminar flow.



4,7

KONVEKSI PAKS

$$\mathrm{Nu} = \frac{hd}{k} = 4.7 = \frac{q_w d}{(T_w - T_b)k}$$

- PP total dari NE: $q = \dot{m} c_p (T_{b_2} - T_{b_1})$

$$\rho = 1.1774\ \mathrm{kg/m^3}$$

$$\dot{m} = (1.1774)\pi(0.0025)^2(3.0) = 6.94 \times 10^{-5}\ \mathrm{kg/s}$$

$$q = (6.94 \times 10^{-5})(1006)(77 - 27) = 3.49\ \mathrm{W}$$

- Hitung fluks kalor (q_w):
- $q = q_w \pi d L = 3.49\ \mathrm{W}$ → $q_w = 2222\ \mathrm{W/m^2}$

$$(T_w - T_b)_{x=L} = \frac{(2222)(0.005)}{(4.7)(0.02814)} = 84^\circ\mathrm{C}$$

KONVEKSI PAKSA

- Suhu pada lubang keluar:

$$T_w|_{x=L} = 84 + 77 = 161^\circ\text{C}$$

- Koef. PP:

$$h_{x=L} = \frac{q_w}{(T_w - T_b)_{x=L}} = \frac{2222}{84} = 26.45\ \text{W/m}^2 \cdot {}^\circ\text{C}$$