14-4. Consider fully developed flow in a circular tube with constant heat rate per unit of tube length. Let the mean flow velocity be 8 m/s. Evaluate the heat-transfer coefficient h for the following cases, and discuss the reasons for the differences:

a. air, 90°C, 1 atm pressure, 2.5-cm-diameter tube;
b. same with 0.6-cm-diameter tube;
c. hydrogen gas, 90°C, 1 atm pressure, 2.5-cm-diameter tube;
d. liquid oxygen, −200°C, 2.5-cm-diameter tube;
e. liquid water, 38°C, 2.5-cm-diameter tube;
f. liquid sodium, 200°C, 2.5-cm-diameter tube;
g. aircraft engine oil, 90°C, 2.5-cm-diameter tube;
h. air, 90°C, 1000 kPa pressure, 2.5-cm-diameter tube.

(H), $V = 8$ m/s

→ for each case, find ρ, D, μ, k_f, Pr

$C_f/2$	Re LB	Re UB	$C_f/2$
	10^4	$5\cdot10^4$	$0.039\,Re^{-0.25}$
	$3\cdot10^4$	10^6	$0.023\,Re^{-0.2}$
	10^4	$5\cdot10^6$	$(2.236\ln Re - 4.639)^{-2}$

$Re = \frac{\rho V D}{\mu}$

$Nu = \frac{hD}{k_f}$

fluid properties evaluated at specified temperatures

Solved using Python code included in submission

a) Air, 90 C, 1 atm
rho = 0.9730, D = 0.025, mu = 0.0000214, k = 0.03024, Pr = 0.713
Re = 9097.71, Nu = 27.30, h = 33.02, solved using Eq. 14-7

b) Air 90 C, 1 atm, D = 0.6cm
rho = 0.9730, D = 0.006, mu = 0.0000214, k = 0.03024, Pr = 0.713
Re = 2183.45, Nu = 4.36, h = 21.99, solved using Eq. 8-17 (Laminar)

c) Hydrogen 90 C, 1 atm
rho = 0.0679, D = 0.025, mu = 0.0000102, k = 20.80077, Pr = 0.706
Re = 1331.73, Nu = 4.36, h = 3630.98, solved using Eq. 8-17 (Laminar)

d) Liquid Oxygen at -200 C
rho = 1222.8750, D = 0.025, mu = 0.0003330, k = 0.17338, Pr = 3.198
Re = 734459.46, Nu = 2231.92, h = 15478.36, solved using Eq. 14-9

e) Liquid Water at 38 C
rho = 992.8800, D = 0.025, mu = 0.0006820, k = 0.62620, Pr = 4.556
Re = 291158.62, Nu = 1185.22, h = 29687.27, solved using Eq. 14-9

f) Liquid Sodium at 200 C
rho = 905.0000, D = 0.025, mu = 0.0004500, k = 81.50000, Pr = 0.007
Re = 402222.22, Nu = 16.41, h = 53507.76, solved using Eq. 14-10

g) Engine Oil at 90 C
rho = 846.0000, D = 0.025, mu = 0.0260800, k = 0.13680, Pr = 407.200
Re = 6487.73, Nu = 49.69, h = 271.88, solved using Eq. 14-8

h) Air at 90 C, 1000 kpa
rho = 9.5850, D = 0.025, mu = 0.0000216, k = 0.03117, Pr = 0.706
Re = 88867.44, Nu = 168.14, h = 209.61, solved using Eq. 14-7

14-5. Consider a 1.20-cm-inside-diameter, 1.8-m-long tube wound by an electric resistance heating element. Let the function of the tube be to heat an organic fuel from 10 to 65°C. Let the mass-flow rate of the fuel be 0.126 kg/s, and let the following average properties be treated as constant:

$$Pr = 10,\ \rho = 753\ \text{kg/m}^3,\ c = 2.10\ \text{kJ/(kg}\cdot\text{K)},\ k = 0.137\ \text{W/(m}\cdot\text{K)}$$

Calculate and plot both tube surface temperature and fluid mean temperature as functions of tube length.

assuming constant heat rate

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at higher Pr numbers, Nu in the entry region is very close to the fully developed value, as seen by the bottom curve in Fig. 14-7

as such, this solution treats the flow as fully developed through the entire tube

$\dot{m} = \rho V A_c$

$$V = \frac{\dot{m}}{\rho A_c} = \frac{4\dot{m}}{\rho\pi D^2} = \frac{4 \cdot 0.126\ \text{kg/s}}{753\ \text{kg/m}^3 \cdot \pi\ (0.012\ \text{m})^2} = 1.48\ \text{m/s}$$

$$\dot{q}'' = \frac{\dot{m} c \Delta T}{A_s} = \frac{0.126\ \text{kg/s} \cdot 2.1\ \text{kJ/kgK} \cdot 55\ \text{K}}{\pi \cdot 0.012\text{m} \cdot 1.8\text{m}} = 214.5\ \text{kW/m}^2$$

$$Re = \frac{\rho V D}{\mu} = \frac{\rho V D C_p}{k\, Pr} = \frac{753\ \text{kg/m}^3 \cdot 1.48\ \text{m/s} \cdot 0.012\text{m} \cdot 2100\ \text{J/kgK}}{0.137\ \text{W/m}\cdot\text{K} \cdot 10} = 20{,}499$$

using equation 14-9 $\quad (0.1 < Pr = 10 < 10^4,\ 10^4 < Re = 20{,}499 < 10^6\ \checkmark)$

$$Nu = 5 + 0.015\, Re^a Pr^b$$

$$a = 0.88 - \frac{0.24}{4 + Pr} = 0.8629$$

$$b = 0.333 + 0.5 e^{-0.6 Pr} = 0.3342$$

$$Nu = 5 + 0.015\,(20{,}499)^{0.8629}\,(10)^{0.3342} = 175.11$$

$$Nu = \frac{hD}{k} \Rightarrow h = \frac{Nu\, k}{D}$$

$$\underline{h = \frac{175.11 \cdot 0.137\ \text{W/m}\cdot\text{K}}{0.012\ \text{m}} = 1{,}999.2\ \text{W/m}^2\text{K}}$$

$$\dot{q}'' = h(T_s - T_m)$$

at $x = 0$, $T_m = 10°C$

$$T_{s0} = \dot{q}''/h + T_m = 214{,}500\ \text{W/m}^2 / 1{,}999.2\ \text{W/m}^2\text{K} + 10°C = 107.3\ °C + 10°C$$

$$\underline{T_{s,0} = 117.3\ °C}$$

because $\dot{q}''$ is constant $\quad T_s - T_m$ is constant. And with A_s = constant, $\frac{dT_m}{dx}$ = constant

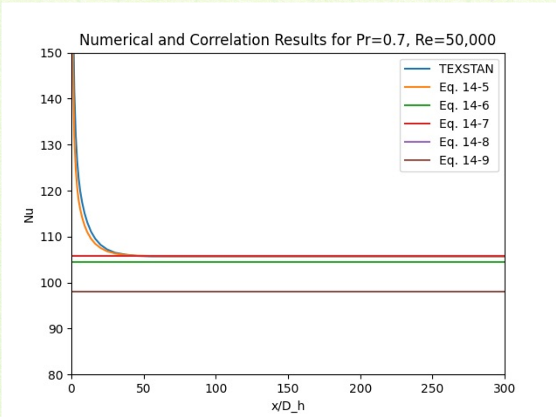
$$T_m(x) = 10°C + \frac{(65-10)°C}{1.8\text{m}} \cdot x$$

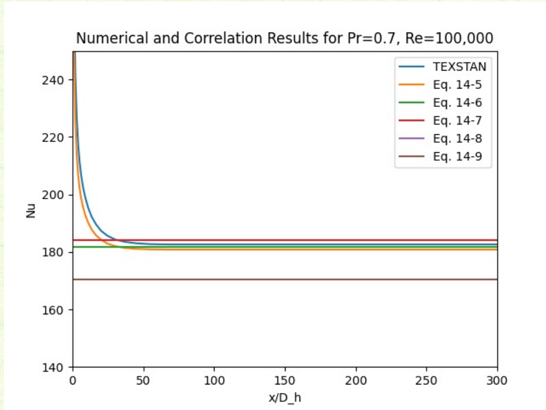
$$\underline{\underline{T_m(x) = 10°C + 30.56\ °C/m \cdot x}} \longleftarrow T_m(x)$$

$$\underline{\underline{T_s(x) = T_m + 107.3°C}} \longleftarrow T_s(x)$$

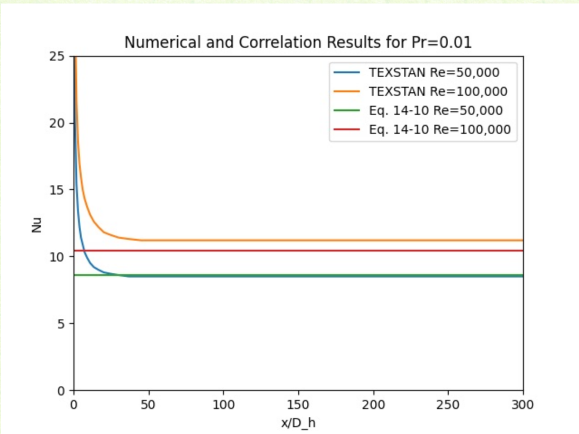
14-13. TEXSTAN *analysis of the turbulent thermal entry flow in a circular tube with constant surface heat flux*: Investigate the entry length region through the thermally fully developed region of flow in a circular tube with diameter Reynolds numbers of 50,000 and 100,000 and fluids corresponding to $\mathrm{Pr} = 0.01$, 0.7, and 10. Evaluate the properties at a fluid entry temperature of 280 K, use constant fluid properties, and do not consider viscous dissipation. Let the pipe diameter be 3.5 cm and the pipe length be 12.0 m. Let the velocity and thermal entry profiles at the inlet to the tube be flat, which can be supplied by using the *kstart*=1 choice in TEXSTAN. Let the energy boundary condition be a constant surface-heat flux of 250 W/m^2. For a turbulence model, choose the hybrid turbulence model composed of a constant eddy viscosity in the outer part of the flow ($\varepsilon_m/\nu = a\mathrm{Re}^b$ with $a = 0.005$ and $b = 0.9$) and a mixing-length turbulence model with the Van Driest damping function ($\kappa = 0.40$ and $A^+ = 26$) in the near-wall region (*ktmu*=7). This hybrid model tends to more closely fit Fig. 13-1, and thus better predict the fully developed friction coefficient and Nusselt number for a given Reynolds number. Choose the constant turbulent Prandtl number model (*ktme*=2) along with a choice for the turbulent Prandtl number, 0.9 is suggested, by setting *fxx*=0.9.

Compare the thermally fully developed Nusselt numbers for $\mathrm{Pr} = 0.7$ with the results from set of Eqs. (14-5) through (14-9). For $\mathrm{Pr} = -0.01$, compare with Eq. (14-10), and for $\mathrm{Pr} = 100$, compare with Eq. (14-8). Feel free to investigate any other attribute of the tube flow. For example, at $\mathrm{Pr} = 0.7$ you can examine a temperature profile at the thermally fully developed state to evaluate the *thermal law of the wall* and compare with Eq. (14-4). Compare your results for how Nusselt number varies in the thermal entry region, as appropriate, with Figs. 14-6, 14-7, and 14-8.

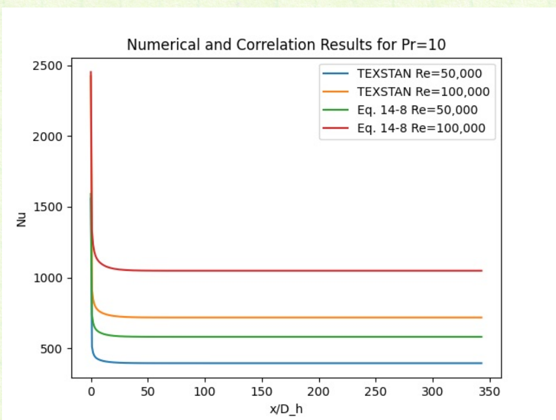


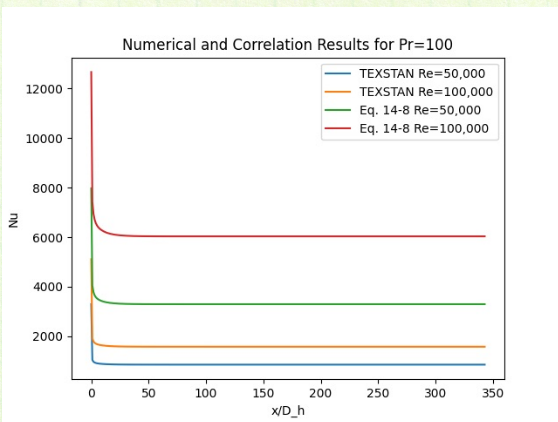


eq. 14-9 has the largest difference in predicted Nu for air
Other equations are more similar to one another and TEXSTAN results

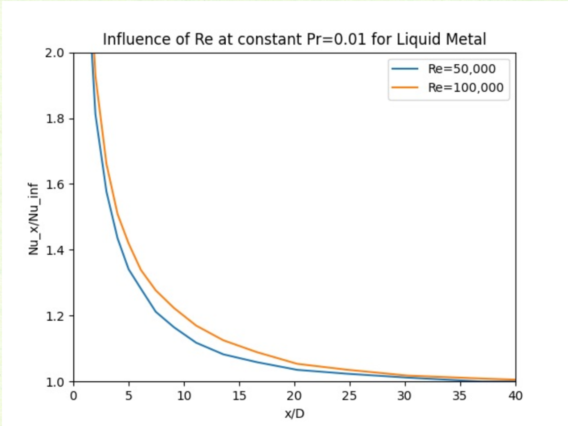


higher Re results in bigger variation between TEXSTAN and Eq. 14-10

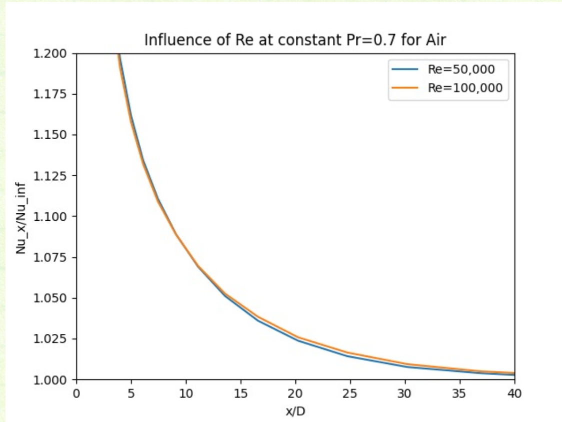




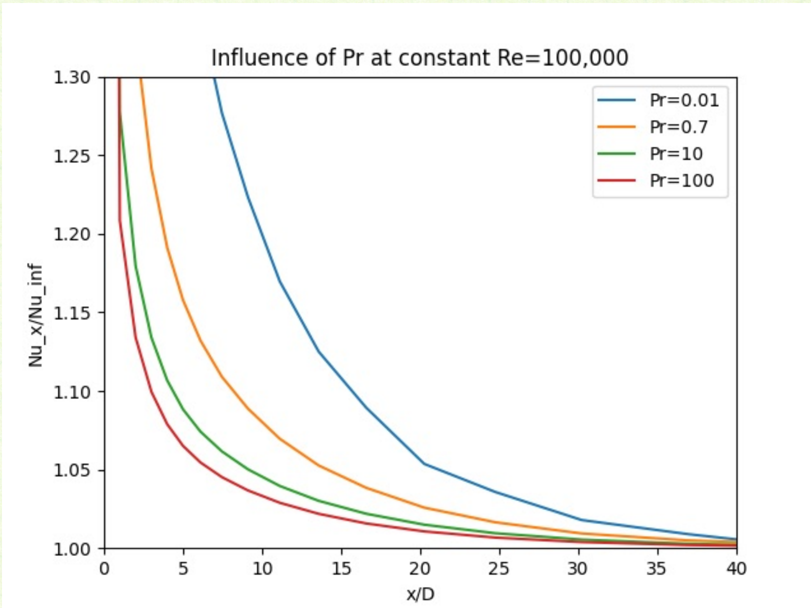
solutions are further apart for higher Pr simulations
correlation equations don't predict as well for higher Pr



Solutions are very close



Re has less of an effect for higher Pr



increased Pr decreases entrance effects