CHAPTER SEVEN

Internal Flow

Having acquired the means to compute convection transfer rates for external flow, we now consider the convection transfer problem for internal flow. an internal flow, such as flow in a pipe, is one for which the fluid is confined by a surface.

7.1 Flow Conditions

Consider laminar flow in a circular tube of radius ro Figure (7.1), where fluid enters the tube with a uniform velocity. We know that when the fluid makes contact with the surface, viscous effects become important, and a boundary layer develops with increasing *x*. This development occurs at the expense of a shrinking inviscid flow

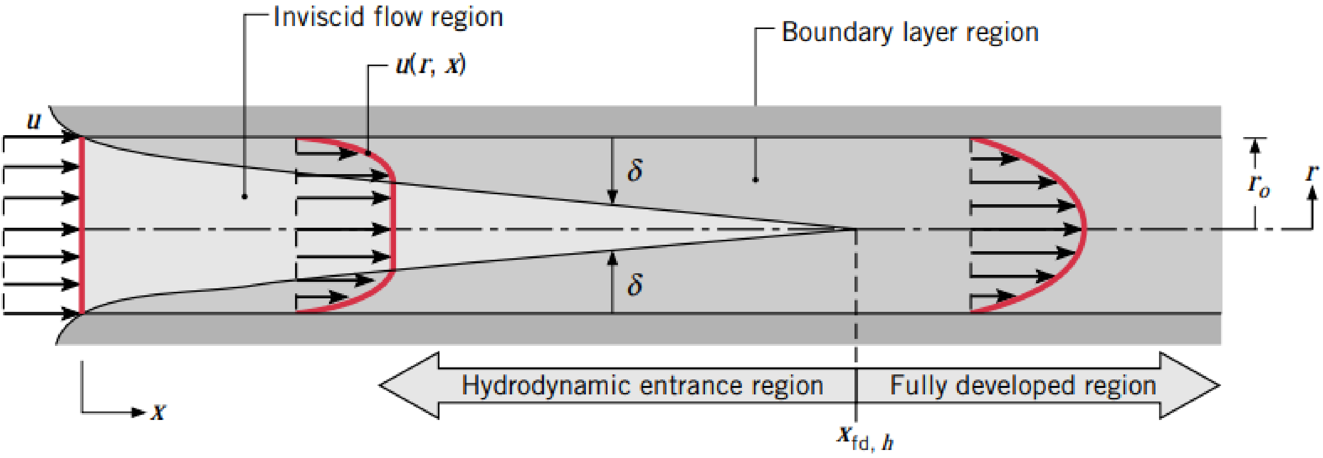


Figure (7.1) Laminar, hydrodynamic boundary layer development in a circular tube.

region and concludes with boundary layer merger at the centerline. Following this merger, viscous effects extend over the entire cross section and the velocity profile no longer changes with increasing *x*. When dealing with internal flows, it is important to be cognizant of the extent of the entry region, which depends on whether the flow is laminar or turbulent. The Reynolds number for flow in a circular tube is defined as

$$Re_D \equiv \frac{\rho u_m D}{\mu} = \frac{u_m D}{\nu} \qquad (7.1)$$

Where: (u_m) is the mean fluid velocity over the tube cross section and (D) is the tube diameter. In a fully developed flow, the critical Reynolds number corresponding to the onset of turbulence is

$Re_{D,c} \approx 2300$

$Re < 2300$	laminar flow
$2300 \leq Re \leq 10{,}000$	transitional flow
$Re > 10{,}000$	turbulent flow

7.2 Mean Velocity and Mean Temperature

Because the velocity varies over the cross section and there is no well-defined free stream, it is necessary to work with a mean velocity um when dealing with internal flows. This velocity is defined such that, when multiplied by the fluid density (ρ) and the cross-sectional area of the tube (A_c), it provides the rate of mass flow through the tube. Hence

$$\dot{m} = \rho u_m A_c \qquad (7.2)$$

For steady, incompressible flow in a tube of uniform cross-sectional area, and (u_m) are constants independent of x. From Eq. (7.1) and (7.2) it is evident that, for flow in a circular tube ($A_c = \pi D^2/4$), the Reynolds number reduces to

$$Re_D = \frac{4\dot{m}}{\pi D \mu} \qquad (7.3)$$

Since the mass flow rate may also be expressed as the integral of the mass flux (ρu) over the cross section

$$\dot{m} = \int_{A_c} \rho u(r, x)\, dA_c \qquad (7.4)$$

it follows that, for incompressible flow in a circular tube

$$u_m = \frac{\int_{A_c} \rho u(r, x)\, dA_c}{\rho A_c} = \frac{2\pi\rho}{\rho \pi r_o^2} \int_0^{r_o} u(r, x)\, r\, dr$$

$$u_m = \frac{2}{r_o^2} \int_0^{r_o} u(r, x)\, r\, dr \qquad (7.5)$$

The foregoing expression may be used to determine (u_m) at any axial location (x) from knowledge of the velocity profile $u(r)$ at that location.

Just as the absence of a free stream velocity requires use of a mean velocity to describe an internal flow, the absence of a fixed free stream temperature necessitates using a mean (or bulk) temperature. To provide a definition of the mean temperature

$$q = \dot{m} c_p (T_{out} - T_{in}) \tag{7.6}$$

Recall that the terms on the right-hand side represent the thermal energy for an incompressible liquid or the enthalpy (thermal energy plus flow work) for an ideal gas, which is carried by the fluid. In developing this equation, it was implicitly assumed that the temperature was uniform across the inlet and outlet cross-sectional areas. In reality, this is not true if convection heat transfer occurs, and we define the mean temperature so that the term $(\dot{m} C_p T_m)$ is equal to the true rate of thermal energy (or enthalpy) advection integrated over the cross section. This true advection rate may be obtained by integrating the product of mass flux (ρu) and the thermal energy (or enthalpy) per unit mass, $(C_p T)$, over the cross section. Therefore, we define T_m from

$$\dot{m} c_p T_m = \int_{A_c} \rho u c_p T dA_c$$

$$T_m = \frac{\int_{A_c} \rho u c_p T dA_c}{\dot{m} c_p} \tag{7.7}$$

For flow in a circular tube with constant (ρ) and (C_p), it follows that

$$T_m = \frac{2}{u_m r_o^2} \int_0^{r_o} u T r dr \tag{7.8}$$

The mean temperature (T_m) is a convenient reference temperature for internal flows, playing much the same role as the free stream temperature (T_∞) for external flows. Accordingly, Newton's law of cooling may be expressed as

$$q_s'' = h(T_s - T_m) \tag{7.9}$$

where (h) is the local convection heat transfer coefficient.

Example (7.1): For flow of a liquid metal through a circular tube, the velocity and temperature profiles at a particular axial location may be approximated as being uniform and parabolic, respectively. That is, $u(r) = C_1$ and $T(r) - T_s = C_2[1 - (r/r_0)^2]$, where C_1 and C_2 are constants. What is the value of the Nusselt number (Nu_D) at this location?

Solution:

$$T(r) - T_s = C_2[1 - (r/r_0)^2] \Rightarrow T(r) = T_s + C_2[1 - (r/r_0)^2]$$

$$q''_s = h(T_s - T_m) \qquad \Rightarrow h = \frac{q''_s}{T_s - T_m}$$

$$T_m = \frac{2}{u_m r_o^2}\int_0^{r_o} uTr\,dr$$

$$T_m = \frac{2C_1}{u_m r_o^2}\int_0^{r_o}\left\{T_s + C_2\left[1 - \left(\frac{r}{r_o}\right)^2\right]\right\}r\,dr$$

From Eq. (7.5) $\quad u_m = C_1$

$$T_m = \frac{2}{r_o^2}\int_0^{r_o}\left\{T_s + C_2\left[1 - \left(\frac{r}{r_o}\right)^2\right]\right\}r\,dr$$

$$T_m = \frac{2}{r_o^2}\left[T_s\frac{r^2}{2} + C_2\frac{r^2}{2} - \frac{C_2}{4}\frac{r^4}{r_o^2}\right]\Bigg|_0^{r_o}$$

$$T_m = \frac{2}{r_o^2}\left(T_s\frac{r_o^2}{2} + \frac{C_2}{2}r_o^2 - \frac{C_2}{4}r_o^2\right) = T_s + \frac{C_2}{2}$$

The heat flux may be obtained from Fourier's law, in which case

$$q''_s = k\frac{\partial T}{\partial r}\bigg|_{r=r_o} = -kC_2 2\frac{r}{r_o^2}\bigg|_{r=r_o} = -2C_2\frac{k}{r_o}$$

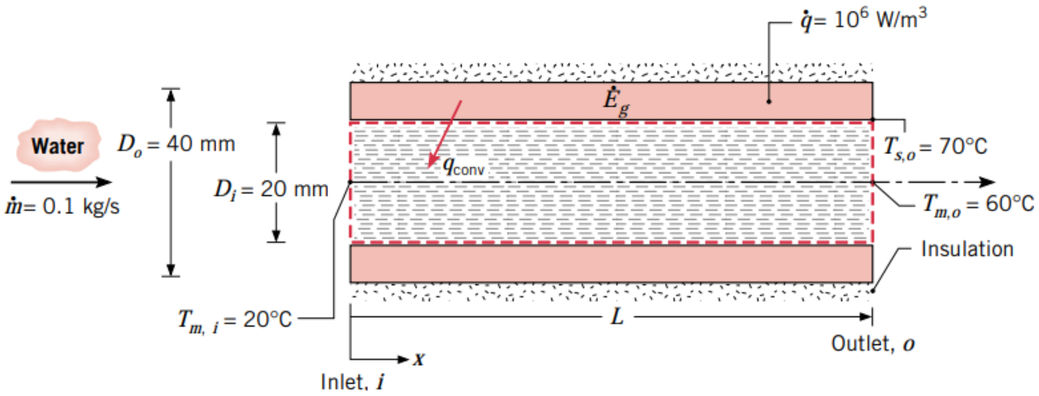
$$h = \frac{q''_s}{T_s - T_m} = \frac{-2C_2(k/r_o)}{-C_2/2} = \frac{4k}{r_o}$$

$$Nu_D = \frac{hD}{k} = \frac{(4k/r_o)\times 2r_o}{k} = 8$$

Example (7.2): A system for heating water from an inlet temperature of ($T_{m,i}$ = 20 °C) to an outlet temperature of ($T_{m,o}$ = 60 °C) involves passing the water through a thick-walled tube having inner and outer diameters of (20 mm) and (40 mm). The outer surface of the tube is well insulated, and electrical heating within the wall provides for a uniform generation rate of (10^6 W/m^3).

1. For a water mass flow rate of (0.1 kg/s), how long must the tube be to achieve the desired outlet temperature?
2. If the surface temperature of the tube is (T_s = 70 °C) at the outlet, what is the local convection heat transfer coefficient at the outlet?

Solution:



$$T_m = \frac{T_{m,i} + T_{m,0}}{2} = \frac{20 + 60}{2} = 40 \text{ °C}$$

From Table (A-9) water properties is $C_p = 4179\ J/kg.K.$

1. Since the outer surface of the tube is adiabatic, the rate at which energy is generated within the tube wall must equal the rate at which it is convected to the water.

$$\dot{E}_g = q_{\text{conv}}$$

$$\dot{E}_g = \dot{q}\frac{\pi}{4}(D_o^2 - D_i^2)L$$

$$\dot{q}\frac{\pi}{4}(D_o^2 - D_i^2)L = \dot{m}c_p(T_{m,o} - T_{m,i})$$

$$10^6 * \frac{\pi}{4} * (0.04^2 - 0.02^2)L = 0.1 * 4179(60 - 20)$$

$$L = 17.7\ m$$

2. To find the local convection heat transfer coefficient at the outlet

$$q''A = \dot{q}V$$

$$q''(\pi D_i L) = \dot{q} * \frac{\pi}{4}\left(D_0^2 - D_i^2\right)L$$

$$q'' = \frac{\left[\dot{q} * \frac{\pi}{4}\left(D_0^2 - D_i^2\right)L\right]}{(\pi D_i L)} = \frac{\dot{q}\left(D_0^2 - D_i^2\right)}{4D_i}$$

$$q'' = \frac{10^6 * (0.04^2 - 0.02^2)}{4 * 0.02}$$

$$q'' = 1.5 \times 10^4\ \ W/m^2$$

$$q'' = h_0\left(T_{s,0} - T_{m,0}\right)$$

$$1.5 \times 10^4 = h_0(70 - 60)$$

$$h_0 = 1500\ W/m^2.K$$

7.3 Laminar Flow in Circular Tubes

For constant heat flux:

In a circular tube characterized by uniform surface heat flux and laminar, fully developed conditions, the Nusselt number is a constant, independent of (Re_D), (Pr), and axial location, so that

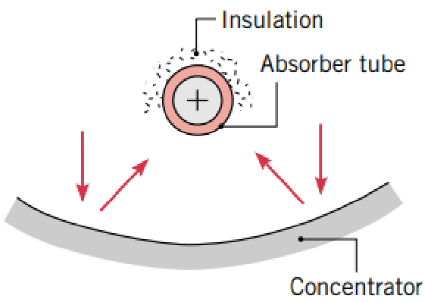
$$Nu_D \equiv \frac{hD}{k} = 4.36 \qquad \text{for} \quad q''_s = \text{constant} \qquad (7.10)$$

For constant temperature:

In a circular tube characterized by uniform surface temperature and laminar, fully developed conditions, the Nusselt number is a constant, independent of (Re_D), (Pr), and axial location, so that

$$Nu_D = \frac{hD}{k} = 3.66 \qquad \text{for } T_s = \text{constant} \qquad (7.11)$$

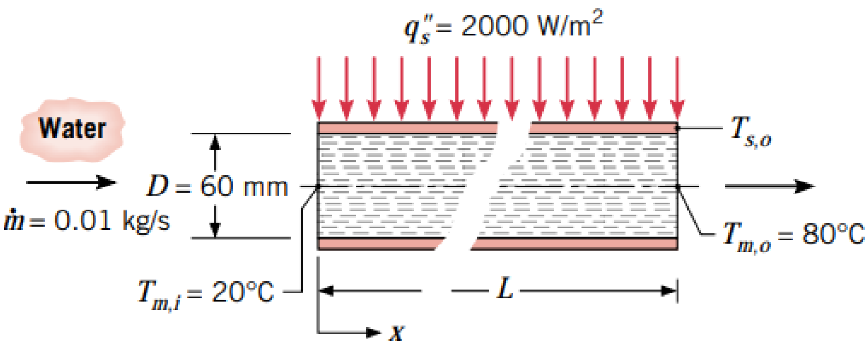
Example (7.3): One concept used for solar energy collection involves placing a tube at the focal point of a parabolic reflector and passing a fluid through the tube. The net effect of this arrangement may be approximated as one of creating a condition of uniform heating at the surface of the tube. That is, the resulting heat flux to the fluid may be assumed to be a constant along the circumference and axis of the tube. Consider operation with a tube of diameter (D = 60 mm) on a sunny day for which (2000 W/m^2).



1. If pressurized water enters the tube at (0.01 kg/s) and ($T_{m,i}$ = 20 °C), what tube length (L) is required to obtain an exit temperature of (80 °C)?
2. What is the surface temperature at the outlet of the tube, where fully developed conditions may be assumed to exist?

Take $k = 0.670\, W/m.K,\quad \mu = 352\ \times 10^{-6}\, N.s/m^2\ and\ Pr = 2.2.$

Solution:



$$T_m = \frac{T_{m,i} + T_{m,0}}{2} = \frac{20 + 80}{2} = 50\ °C$$

From Table (A-9) water properties is $C_p = 4181 J/kg.K.$

1. To find the tube length (L) is required to obtain an exit temperature of (80 °C).

$$q = q''A$$

$$\dot{m}C_p\left(T_{m,0} - T_{m,i}\right) = q''(\pi DL)$$

$$0.01 * 4181 * (80 - 20) = 2000 * \pi * 0.06L$$

$$L = \ 6.65\ m$$

2. To find the surface temperature at the outlet of the tube

$$Re_D = \frac{4\dot{m}}{\pi D \mu} = \frac{4 * 0.01}{\pi * 0.06 * 352 * 10^{-6}} = 601$$

The flow is laminar

$$Nu_D = \frac{hD}{K} = 4.36$$

$$h = \frac{4.36K}{D} = \frac{4.36 * 0.67}{0.06}$$

$$h = 48.7\ W/m^2.K$$

$$q'' = h\left(T_{s,0} - T_{m,0}\right)$$

$$2000 = 48.7\left(T_{s,0} - 80\right)$$

$$T_{s,0} = 121\ ℃$$

Constant Surface Temperature

Results for the total heat transfer rate and the axial distribution of the mean temperature are entirely different for the constant surface temperature condition.

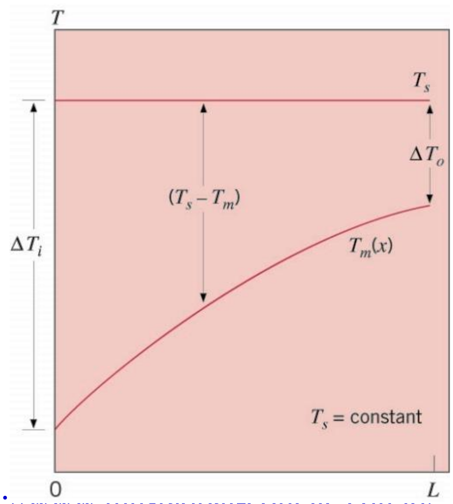
Overall condisions:

$$q_{conv} = \bar{h} A_s \Delta T_{lm} \qquad T_s = \text{constant} \qquad (7.12)$$

where A_s: is the tube surface area ($A_s = PL$).

ΔT_{lm}: is the log mean temperature difference.

$$\Delta T_{lm} = \frac{\Delta T_0 - \Delta T_i}{\ln \Delta T_0 / \Delta T_i} \qquad (7.13)$$



$$\Delta T_0 = T_s - T_{m,0}$$

$$\Delta T_i = T_s - T_{m,i}$$

$$\Delta T_{lm} = \frac{\left(T_s - T_{m,0}\right) - \left(T_s - T_{m,i}\right)}{\ln\left(T_s - T_{m,0}\right)/\left(T_s - T_{m,i}\right)}$$

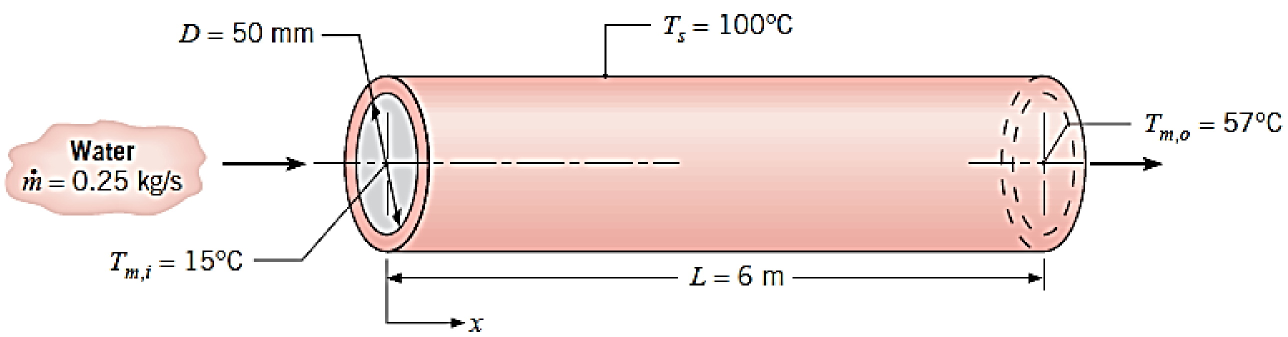
$$\Delta T_{lm} = \frac{T_{m,i} - T_{m,0}}{\ln\left(T_s - T_{m,0}\right)/\left(T_s - T_{m,i}\right)} \qquad (7.14)$$

$$q_{conv} = \dot{m}C_p\left(T_{m,0} - T_{m,i}\right) \qquad (7.15)$$

$$\bar{h} = \frac{\dot{m}C_p}{A_s}\frac{\left(T_{m,0} - T_{m,i}\right)}{\Delta T_{lm}} \qquad (7.16)$$

Example (7.4): Steam condensing on the outer surface of a thin-walled circular tube of diameter (D = 50 mm) and length (L = 6 m) maintains a uniform outer surface temperature of (100 °C). Water flows through the tube at a rate of (0.25 kg/s), and its inlet and outlet temperatures are ($T_{m,i}$ = 15 °C) and ($T_{m,o}$ = 57 °C). What is the average convection coefficient associated with the water flow?

Soltion:



$$T_m = \frac{T_{m,i} + T_{m,0}}{2} = \frac{15 + 57}{2} = 36\ ℃$$

From Table (A-9) water properties is $C_p = 4178\, J/kg.K$.

$$\bar{h} = \frac{\dot{m}C_p}{A_s}\frac{\left(T_{m,0} - T_{m,i}\right)}{\Delta T_{lm}} = \frac{\dot{m}C_p}{\pi DL}\frac{\left(T_{m,0} - T_{m,i}\right)}{\Delta T_{lm}}$$

$$\Delta T_{lm} = \frac{\left(T_s - T_{m,0}\right) - \left(T_s - T_{m,i}\right)}{\ln\left(T_s - T_{m,0}\right)/\left(T_s - T_{m,i}\right)}$$

$$\Delta T_{lm} = \frac{(100 - 57) - (100 - 15)}{\ln(100 - 57)/(100 - 15)}$$

$$\Delta T_{lm} = 61.6\ ℃$$

$$\bar{h} = \frac{0.25 * 4178}{\pi * 0.05 * 6} \frac{(57 - 15)}{61.6}$$

$$\bar{h} = 755\ W/m^2.K$$

7.4 Turbulent Flow in Circular Tubes

The Dittus–Boelter equation is a slightly different and preferred and is of the form

$$Nu_D = 0.023 Re_D^{4/5}\ Pr^n \qquad (7.17)$$

where $n = 0.4$ for heating $(Ts > Tm)$,

and $n = 0.3$ for cooling $(Ts < Tm)$.

These equations have been confirmed experimentally for the range of conditions

$$\begin{bmatrix} 0.7 \lesssim Pr \lesssim 160 \\ Re_D \gtrsim 10{,}000 \\ \dfrac{L}{D} \gtrsim 10 \end{bmatrix}$$

One correlation, valid over a large Reynolds number range including the transition region, is provided by Gnielinski:

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \qquad (7.18)$$

Where (f) the friction factor may be obtained from the Moody diagramas shown in Figure (7.2), or, for smooth tubes from the equation (7.19) if

$$3000 \lesssim Re_D \lesssim 5 \times 10^6$$

$$f = (0.790 \ln Re_D - 1.64)^{-2} \qquad (7.19)$$

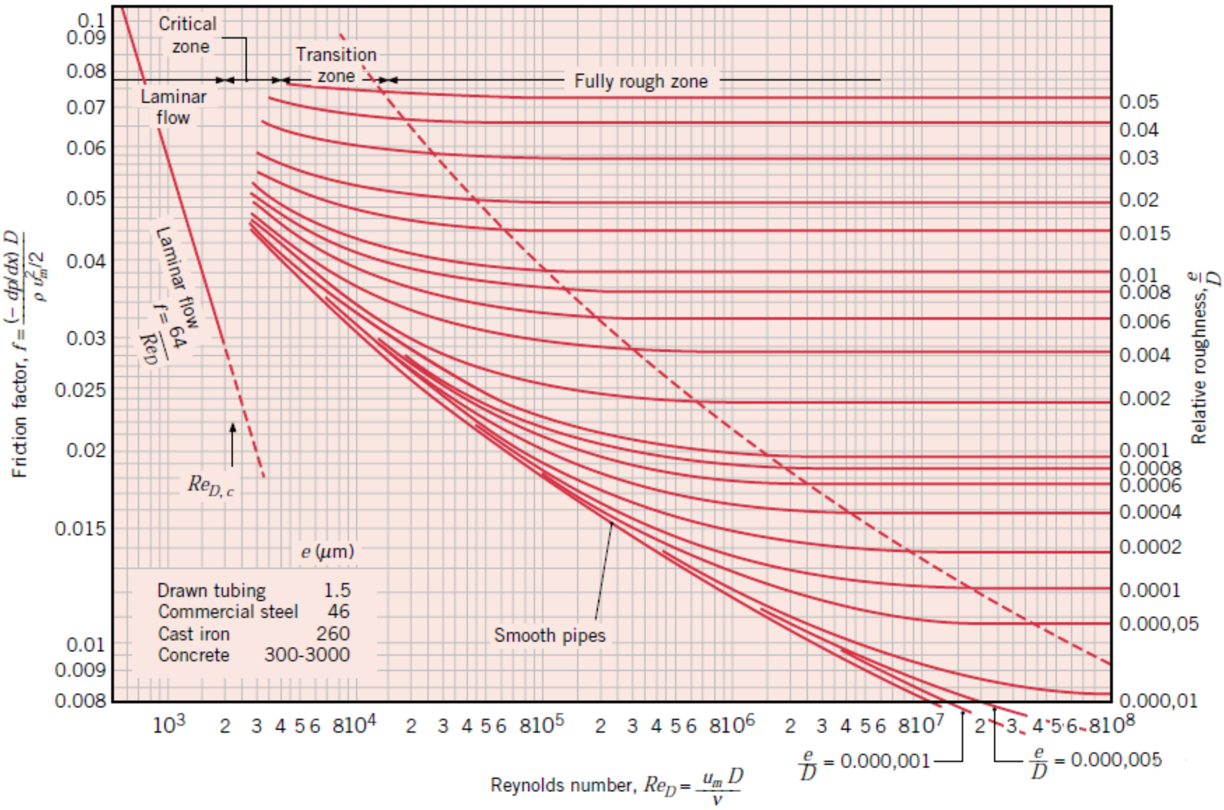
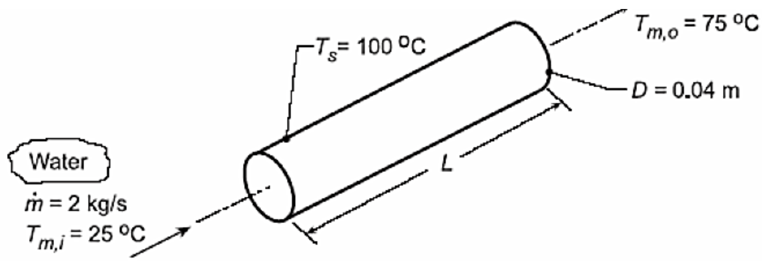


Figure (7.2) Friction Factor for Fully Developed Flow in a Circular Tube.

Example (7.5): Water flowing at (2 kg/s) through a (40 mm) diameter tube is to be heated from (25 to 75 °C) by maintaining the tube surface temperature at (100 °C). What is the required tube length for these conditions? Fully developed conditions may be assumed to exist.



Solution:

$$T_m = \frac{T_{m,i} + T_{m,0}}{2} = \frac{25 + 75}{2} = 50\ °C$$

From Table (A-9) water properties is

$C_p = 4181\ J/kg.K$ $\qquad \mu = 547 \times 10^{-6} N.s/m^2$

$k = 0.643\ W/m.K$ $\qquad Pr = 3.56$

$$Re_D = \frac{4\dot{m}}{\pi D \mu} = \frac{4 * 2}{\pi * 0.04 * 547 \times 10^{-6}}$$

$$Re_D = 1.16 \times 10^5$$

Hence the flow is turbulent and assuming fully developed then

$$Nu_D = 0.023 Re_D^{4/5} Pr^n$$

where $n = 0.4$ for heating $(Ts > Tm)$

$$\overline{Nu_D} = 0.023 * (1.16 \times 10^5)^{\frac{4}{5}} * (3.56)^{0.4}$$

$$\overline{Nu_D} = \frac{\bar{h}D}{k} = 430.4 \Rightarrow \bar{h} = 430.4 * \frac{0.643}{0.04}$$

$$\bar{h} = 6919\, W/m^2\,.K$$

$$\bar{h} = \frac{\dot{m}C_p}{\pi DL}\frac{(T_{m,0} - T_{m,i})}{\Delta T_{lm}} \Rightarrow L = \frac{\dot{m}C_p}{\pi D\bar{h}}\frac{(T_{m,0} - T_{m,i})}{\Delta T_{lm}}$$

$$\Delta T_{lm} = \frac{\Delta T_0 - \Delta T_i}{\ln \Delta T_0 / \Delta T_i}$$

$$\Delta T_{lm} = \frac{T_{m,i} - T_{m,0}}{\ln (T_s - T_{m,0})/(T_s - T_{m,i})}$$

$$\Delta T_{lm} = \frac{25 - 75}{\ln (100 - 75)/(100 - 25)}$$

$$\Delta T_{lm} = 45.5\ ^\circ\mathrm{C}$$

$$L = \frac{2 * 4181}{\pi * 0.04 * 6919}\frac{(75 - 25)}{45.5}$$

$$L = 10.6\, m$$

7.5 Pressure Gradient and Friction Factor in Fully Developed Flow

The engineer is frequently interested in the pressure drop needed to sustain an internal flow because this parameter determines pump or fan power requirements. To determine the pressure drop, it is convenient to work with the Moody (or Darcy) friction factor, which is a dimensionless parameter defined as

$$f \equiv \frac{-(dp/dx)D}{\rho u_m^2/2} \qquad (7.20)$$

This quantity is not to be confused with the friction coefficient, sometimes called the Fanning friction factor, which is defined as

$$C_f \equiv \frac{\tau_s}{\rho u_m^2/2}$$

since

$$\tau_s = -\mu \frac{du}{dr})_{r=r_o}$$

it follows that

$$C_f = \frac{f}{4}$$

for fully developed laminar flow,

$$f = \frac{64}{Re_D} \qquad (7.21)$$

Note that f, hence dp/dx, is a constant in the fully developed region. From Equation (7.20) the pressure drop ($\Delta p = p_1 - p_2$) associated with fully developed flow from the axial position (x_1) to (x_2) may then be expressed as

$$\Delta p = -\int_{p_1}^{p_2} dp = f\frac{\rho u_m^2}{2D}\int_{x_1}^{x_2} dx$$

$$\Delta p = f\frac{\rho u_m^2}{2D}(x_2 - x_1) = f\frac{L}{D}\frac{\rho u_m^2}{2} \qquad (7.22)$$

where (f) is obtained from Figure (7.2) or from Equation (7.21) for laminar flow and from Equation (7.19) for turbulent flow in smooth tubes. The pump or fan power required to overcome the resistance to flow associated with this pressure drop may be expressed as

$$P = (\Delta p)\dot{\forall} \qquad (7.23)$$

where ($\dot{\forall}$) is the volumetric flow rate may, for an incompressible fluid be expressed as

$$\dot{\forall} = \dot{m}/\rho$$

8.6 Non-circular Tubes and the Concentric Tube Annulus

Although we have thus far restricted our consideration to internal flows of circular cross section, many engineering applications involve convection transport in noncircular tubes.

At least to a first approximation, however, many of the circular tube results may be applied by using an effective diameter as the characteristic length. It is termed the hydraulic diameter and is defined as

$$D_h \equiv \frac{4A_c}{P} \tag{7.24}$$

where A_c: is the flow cross-sectional area.

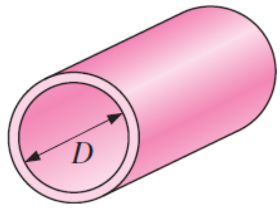
P: is the wetted perimeter.

It is this diameter that should be used in calculating parameters such as Re_D and Nu_D.

The turbulent flow, which still occurs if $Re_D > 2300$.

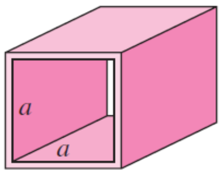
Circular tubes:

$$D_h = \frac{4A_c}{p} = \frac{4\pi D^2/4}{\pi D} = D$$



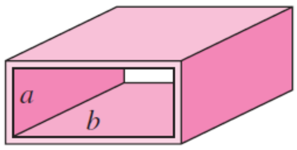
Square duct:

$$D_h = \frac{4a^2}{4a} = a$$



Rectangular duct:

$$D_h = \frac{4ab}{2(a+b)} = \frac{2ab}{a+b}$$



Example (7.6): Water at (40 °F) ($\rho = 62.42\ lbm/ft^3$) and ($\mu = 0.00104\ lbm/ft.s$) is flowing in a (0.01 ft) diameter ($30\ ft$) long pipe steadily at an average velocity of ($3\ ft/s$). Determine the pressure drop and the pumping power requirement to overcome this pressure drop.

Solution:

$$Re_D = \frac{\rho u_m D}{\mu}$$

$$Re_D = \frac{62.42 * 3 * 0.01}{0.00104} = 1800$$

$$Re_D < 2300 \Rightarrow laminar\ flow$$

$$f = \frac{64}{Re_D} = \frac{64}{1800} = 0.0355$$

$$\Delta P = f \frac{L}{D} \frac{\rho u_m^2}{2}$$

$$\Delta P = 0.0355 * \frac{30}{0.01} * \frac{62.42 * 3^2}{2} * \frac{1}{32.174}$$

$$\Delta P = 930\, Ib_f/ft^2$$

$$\dot{\forall} = u_m A_c = u_m \left(\frac{\pi}{4} D^2\right)$$

$$\dot{\forall} = 3 * \frac{\pi}{4} (0.01)^2 = 0.000236\, ft^3/s$$

$$P = \dot{\forall} \Delta P = 0.00236 * 930$$

$$P = 0.219\, ft.Ib_f/s$$

$$1W = 0.737 ft.Ib_f/s$$

$$P = \frac{0.219}{0.737} = 0.3\ W$$

Home Work (7)

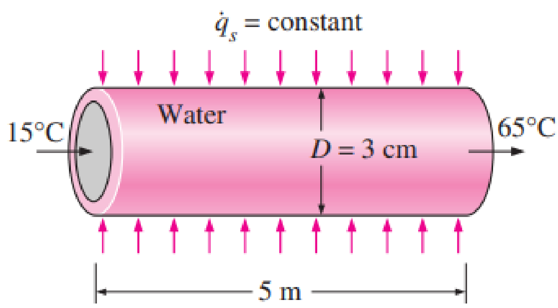
1- Atmospheric air enters the heated section of a circular tube at a flow rate of (0.005 *kg/s*) and a temperature of (20 °C). The tube is of diameter (D = 50 *mm*), and fully developed conditions with (h = 25 $W/m^2.K$) exist over the entire length of (L = 3 *m*). For the case of uniform surface heat flux at (1000 W/m^2) , determine the total heat transfer rate (q) and the mean temperature of the air leaving the tube ($T_{m,o}$). What is the value of the surface temperature at the tube inlet ($T_{s,i}$) and outlet ($T_{s,o}$)? assume (C_p = *1.008 kJ/kg.k*).

2- Velocity and temperature profiles for laminar flow in a tube of radius (r_o = 10 mm) have the form

$$u(r) = 0.1[1 - (r/r_o)^2]$$
$$T(r) = 344.8 + 75.0(r/r_o)^2 - 18.8(r/r_o)^4$$

with units of m/s and K, respectively. Determine the corresponding value of the mean (or bulk) temperature, (T_m), at this axial position.

3- Water is to be heated from (15 °C) to (65 °C) as it flows through a (3 cm) internaldiameter (5 m) long tube shown in figure below. The tube is equipped with an electric resistance heater that provides uniform heating throughout the surface of the tube. The outer surface of the heater is well insulated, so that in steady operation all the heat generated in the heater is transferred to the water in the tube. If the system is to provide hot water at a rate of (10 L/min), determine the power rating of the resistance heater. Also, estimate the inner surface temperature of the pipe at the exit. If $Re > 2300$ take $Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$



4- Determine the mean velocity in the pipe, if the velocity profile in fully developed laminar flow in a circular pipe, is given by

$$u(r) = 4(1 - r^2/r_0^2)$$

Home Work (8)

1- A longe pipeline transfered oil, the length of the pipe is (L =100 km), the pipe diameter of (D = 1.2 m) and with oil flow rate of (500 kg/s). The oil properties are ($\rho = 900\ kg/m^3$), ($C_p = 2000\ J/kg.K$), ($\mu = 0.765\ N.s/m^2$). Calculate the pressure drop and the flow work (power).

2- Atmospheric air enters a (10 m) long, (150 mm) diameter uninsulated heating duct at (60 °C) and (0.04 kg/s). The duct surface temperature is approximately constant at (T_s=15 °C). What are the outlet air temperature, the heat rate, and pressure drop for these conditions?

3- Consider a thin-walled tube of (10 mm) diameter and (2 m) length. Water enters the tube from a large reservoir at (0.2 kg/s) and ($T_{m,i}$ = 47 °C). If the tube surface is maintained at a uniform temperature of (27 °C), what is the outlet temperature of the water, ($T_{m,o}$)? To obtain the properties of water, assume an average mean temperature of (T_m=300 K).