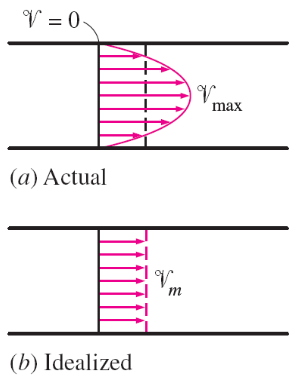
HEAT TRANSFER
Convection Heat Transfer – Internal Forced Flow

Internal flow refers to fluid flow in a pipe – the fluid is confined. Fluid flows in circular pipes or noncircular cross section called ducts.

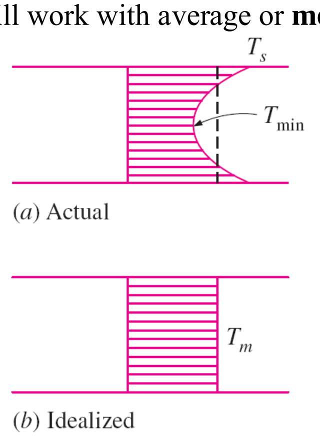
Mean Velocity and Mean Temperature

In external flow, the free stream velocity is used in the analysis but for internal flow there is no free stream velocity.

In a pipe, the fluid varies from zero at the surface to a maximum value at the center. We will work with the average or **mean velocity, u_m**.



Similarly with temperature, we will work with average or **mean temperature, T_m**.



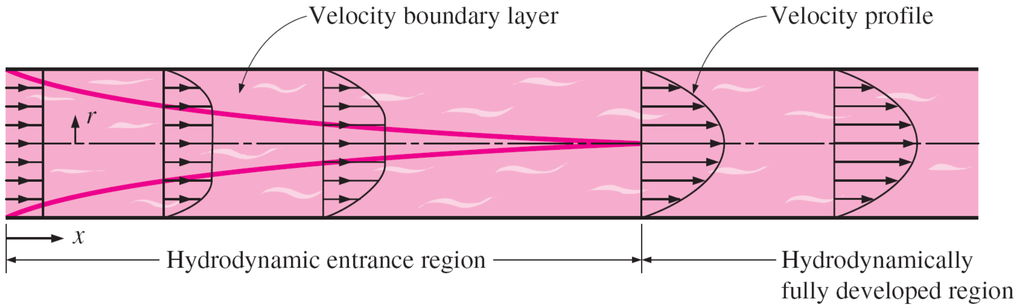
Laminar and Turbulent Flow in Tubes

Flow in tubes can also be categorized as laminar or turbulent and it can be determined by the Reynolds number:

$$\mathrm{Re} = \frac{u_m D}{\upsilon}$$

Laminar flow: Re < 2,300
Turbulent flow: Re > 10,000
Between 2,300 and 10,000 is the transition region.

The Entrance Region

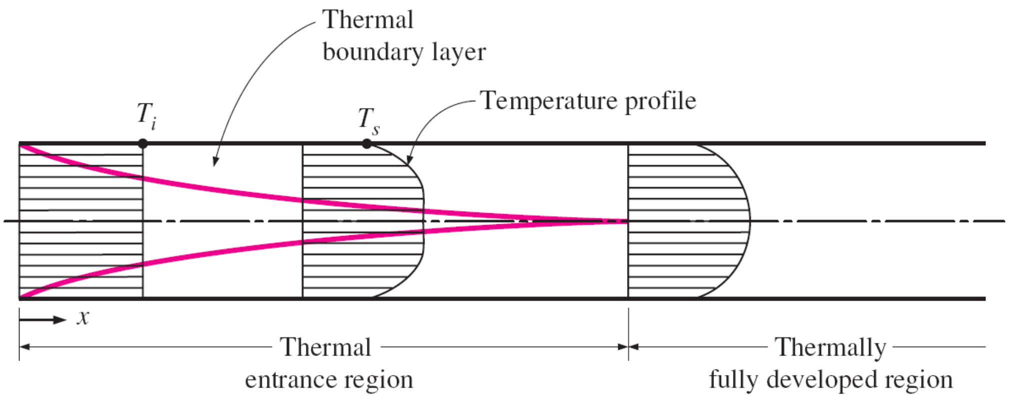


The region from the tube inlet to the point at which the boundary layer merges at the centerline is called the **hydrodynamic entrance region,** and the length of this region is called the **hydrodynamic entry length** L_h.

The region beyond the entrance region in which the velocity profile is fully developed and remains unchanged is called the **hydrodynamically fully developed region.**

Flow in the entrance region is called **hydrodynamically developing flow** since this is the region where the velocity profile develops.

The velocity profile in the fully developed region is *parabolic* in laminar flow and somewhat *flatter* in turbulent flow due to eddy motion in radial direction.



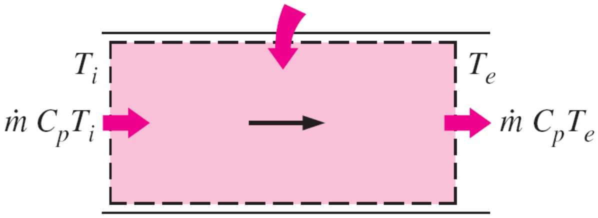
The region of flow over which the thermal boundary layer develops and reaches the tube center is called the **thermal entrance region,** and the length of this region is called the **thermal entry length** L_t.

The region beyond the thermal entrance region is called the **thermally fully developed region.**

Flow in the thermal entrance region is called **thermally developing flow** since this is the region where the temperature profile develops.

The region in which the flow is both hydrodynamically and thermally developed and thus both the velocity and dimensionless temperature profiles remain unchanged is called **fully developed flow.** The fully developed flow can be laminar or turbulent.

General Thermal Analysis



The conservation of energy equation for the steady flow of a fluid in a tube can be expressed as:

$$q = \dot{m} C_p \left(T_e - T_i\right) \qquad \text{(kJ)}$$

Where T_i and T_e is the inlet and exit temperature respectively, m is the mass flow rate and C_p is the specific heat capacity of the fluid at constant pressure.

When considering internal flow problems, it is a necessary to first establish if the problem involves **constant surface temperature** (phase change process) or **constant surface heat flux** (electrical resistance heating).

Constant Surface Heat Flux

$q''_{conv} = constant$

See tutorial question 8

Constant Surface Heat Flux

$T_s = constant$

$$q_{conv} = \bar{h} A_s \Delta T_m$$

Where, $\Delta T_m = \dfrac{\Delta T_o - \Delta T_i}{\ln\left(\Delta T_o / \Delta T_i\right)}$

See tutorial question 9

Flow in Circular Tubes – Fully Developed Region

Laminar

Constant surface heat flux $Nu_D = 4.36$

Constant surface temperature $Nu_D = 3.66$

For the above correlation, $Nu_D = \frac{hD}{k}$, k is evaluated at T_m

Turbulent

Constant surface heat flux or constant surface temperature:

$Nu_D = 0.023 \mathrm{Re}_D^{4/5} \mathrm{Pr}^n$ Dittus – Boelter correlation

Conditions:
All properties evaluated at T_m
Turbulent ($Re_D > 10{,}000$),
Fully developed flow,
$0.6 \le Pr \le 160 \ge$
$L/D \ge 10$,
n = 0.4 for $T_s > T_m$
n = 0.3 for $T_s < T_m$

The Dittus – Boelter correlation can be used to evaluate average Nusselt number but evaluation must be done at $\overline{T_m} = \frac{T_{m,i} + T_{m,o}}{2}$