Fluid Mechanics: Fundamentals of Fluid Mechanics, 7th Edition,
Bruce R. Munson. Theodore H. Okiishi. Alric P. Rothmayer
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Lecture- 06
Fluid Dynamics

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Learning Objectives

- After completing this Lecture, you should be able to:
- 1.Identify differences between:
  - steady/unsteady
  - uniform/non-uniform
  - compressible/incompressible flow
- 2.Demonstrate streamlines and stream tubes
- 3.Introduce the Continuity principle

Outline

- Overview
- Flow Classification
- Streamlines
- Streamtubes
- Flow rate

- **Fluid dynamics:**
- The analysis of fluid in motion . Fluid motion can be predicted in the same way as the motion of solids . By use of the fundamental laws of physics and the physical properties of the fluid

- **Some fluid flow is very complex:**
  - Spray behind a car
  - waves on beaches;
  - hurricanes and tornadoes
  - any other atmospheric phenomenon

- All can be analyzed with varying degrees of success (in some cases hardly at all!). There are many common situations which analysis gives very accurate predictions

Flow Classification

- Fluid flow may be classified under the following headings

- **uniform:** Flow conditions (velocity, pressure, cross-section or depth) are the same at every point in the fluid.
- **non-uniform:** Flow conditions are not the same at every point.

- **steady:** Flow conditions may differ from point to point but DO NOT change with time.
- **unsteady:** Flow conditions change with time at any point.

- Fluid flowing under normal circumstances - a river for example - conditions vary from point to point we have non-uniform flow.

- If the conditions at one point vary as time passes then we have unsteady flow.

Flow Classification

Combining these four gives

- **Steady uniform flow:** Conditions do not change with position in the stream or with time. E.g. flow of water in a pipe of constant diameter at constant velocity.

- **Steady non-uniform flow:** Conditions change from point to point in the stream but do not change with time. E.g. Flow in a tapering pipe with constant velocity at the inlet.

- **Unsteady uniform flow:** At a given instant in time the conditions at every point are the same, but will change with time. E.g. A pipe of constant diameter connected to a pump pumping at a constant rate which is then switched off.

- **Unsteady non-uniform flow:** Every condition of the flow may change from point to point and with time at every point.E.g. Waves in a channel.

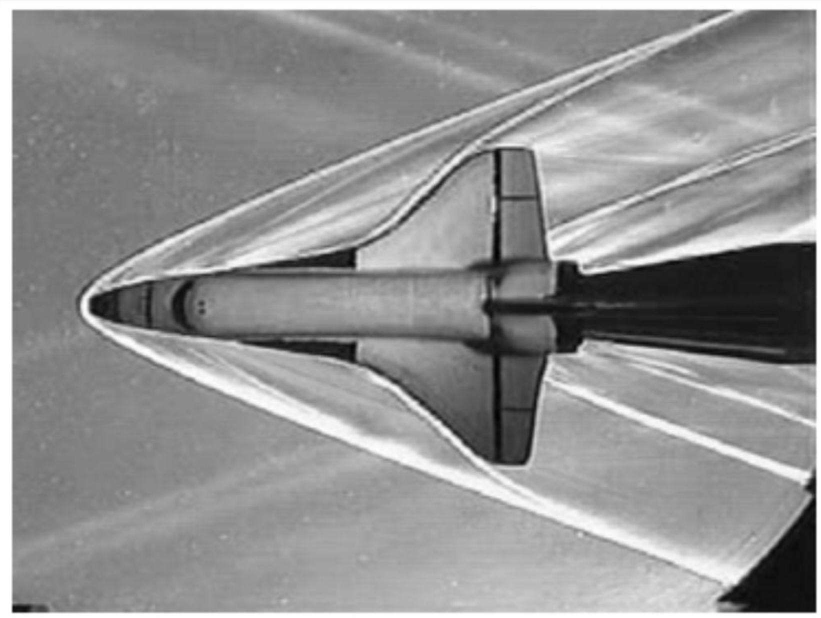
Flow Classification

Compressible versus Incompressible Flow

- **Incompressible flow:** If the density of flowing fluid remains nearly constant throughout (e.g., liquid flow).
- **Compressible flow:** If the density of fluid changes during flow (e.g., high-speed gas flow) When analysing rockets, spacecraft, and other systems that involve high speed gas flows, the flow speed is often expressed by **Mach number**

$$\mathrm{Ma} = \frac{V}{c} = \frac{\text{Speed of flow}}{\text{Speed of sound}}$$

Ma = 1 Sonic flow
Ma < 1 Subsonic flow
Ma > 1 Supersonic flow
Ma >> 1 Hypersonic flow

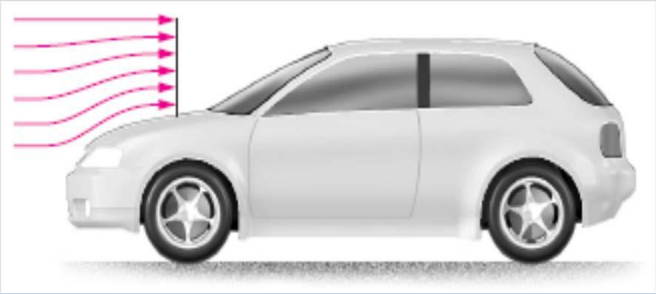


Schlieren image of a small model of the space shuttle orbiter being tested at Mach 3 in the supersonic wind tunnel of the Penn State Gas Dynamics Lab. Several *oblique shocks* are seen in the air surrounding the spacecraft.

Flow Classification

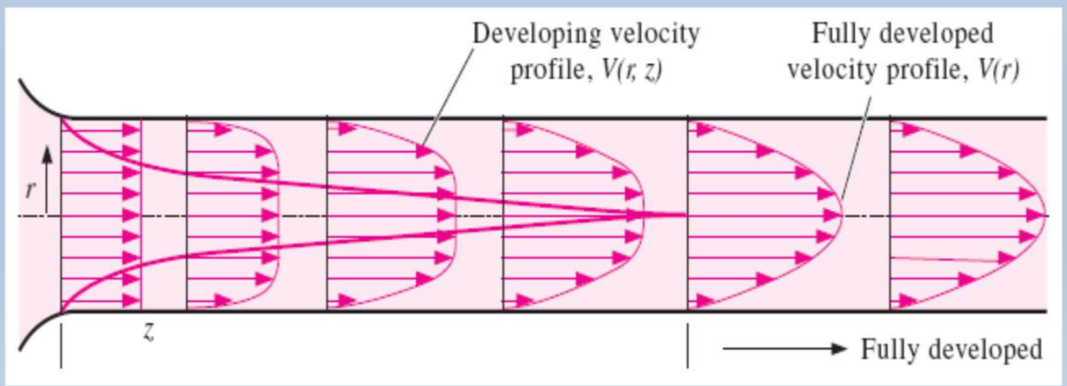
One-, Two-, and Three-Dimensional Flows

- A flow field is best characterized by its velocity distribution.
- A flow is said to be one-, two-, or three dimensional if the flow velocity varies in one, two, or three dimensions, respectively.
- However, the variation of velocity in certain directions can be small relative to the variation in other directions and can be ignored.



Flow over a car antenna is approximately two dimensional except near the top and bottom of the antenna.

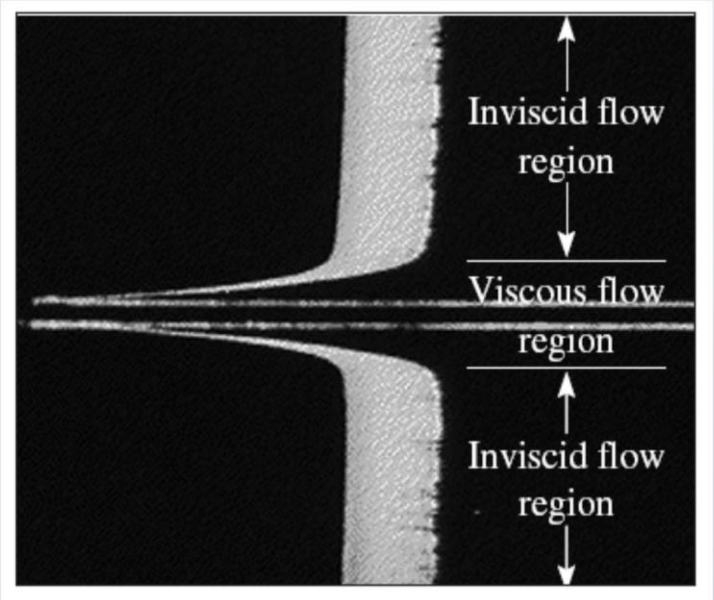
The development of the velocity profile in a circular pipe. $V = V(r, z)$ and thus the flow is two-dimensional in the entrance region, and becomes one-dimensional downstream when the velocity profile fully develops and remains unchanged in the flow direction, $V = V(r)$.



Flow Classification

Viscous versus Inviscid Regions of Flow

- **Viscous flows:** Flows in which the frictional effects are significant.
- **Inviscid flow regions:** In many flows of practical interest, there are *regions* (typically regions not close to solid surfaces) where viscous forces are negligibly small compared to inertial or pressure forces.

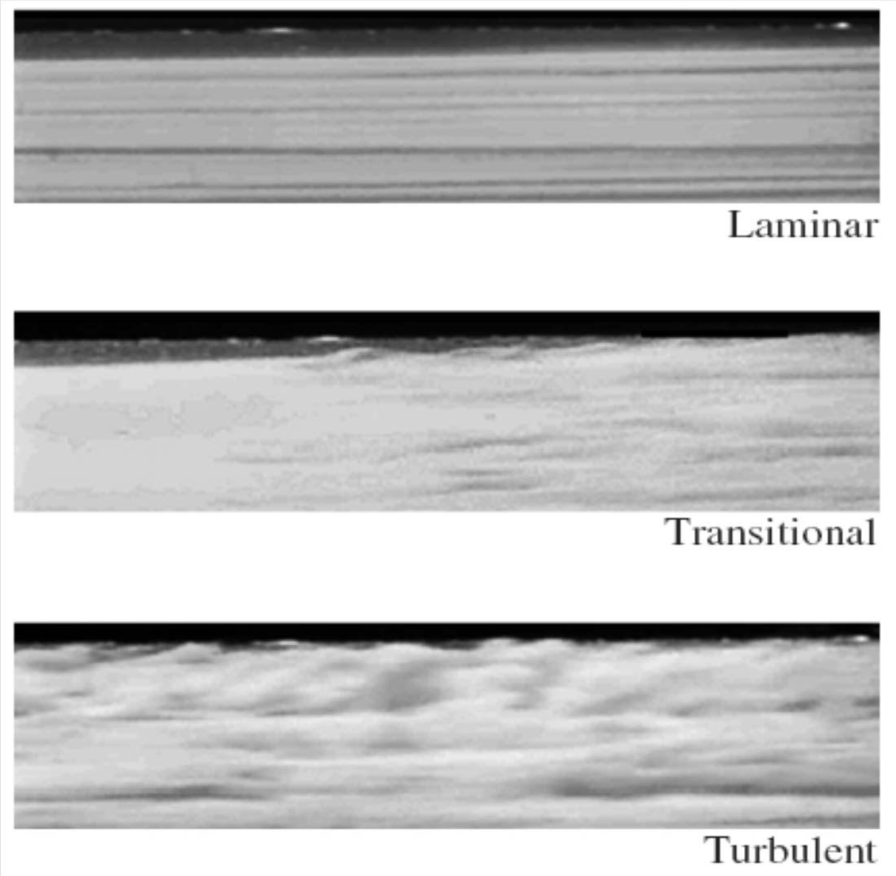


The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).

Flow Classification

Laminar versus Turbulent Flow

- **Laminar flow:** The highly ordered fluid motion characterized by smooth layers of fluid. The flow of high-viscosity fluids such as oils at low velocities is typically laminar.
- **Turbulent flow:** The highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations. The flow of low viscosity fluids such as air at high velocities is typically turbulent.
- **Transitional flow:** A flow that alternates between being laminar and turbulent.



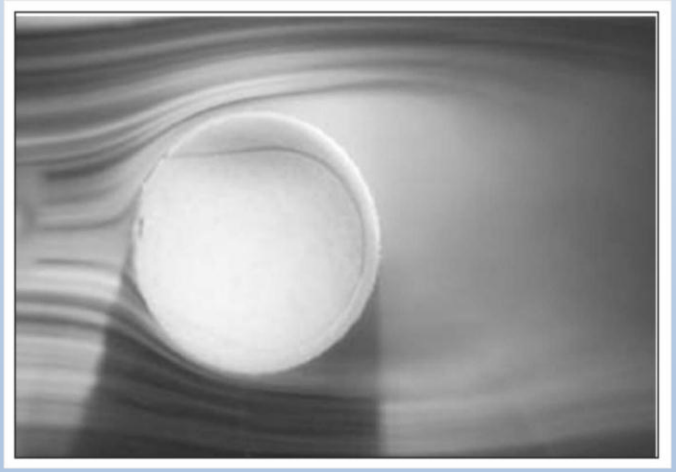
Laminar, transitional, and turbulent flows.

Flow Classification

Internal versus External Flow

External flow: The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe

Internal flow: The flow in a pipe or duct if the fluid is completely bounded by solid surfaces.

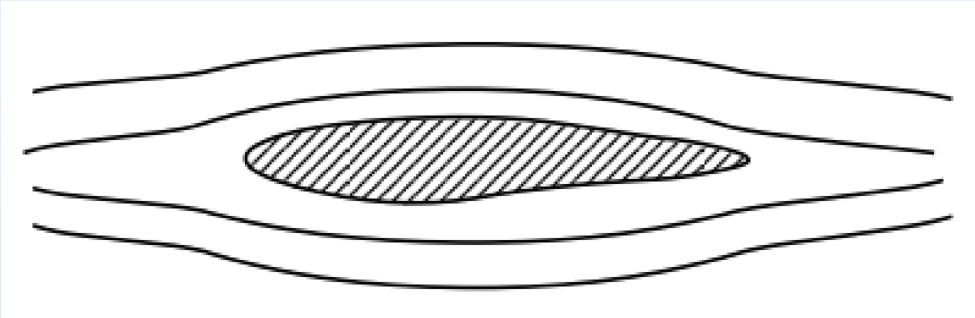


External flow over a tennis ball, and the turbulent wake region behind.

- Water flow in a pipe is internal flow, and airflow over a ball is external flow .
- The flow of liquids in a duct is called *openchannel flow* if the duct is only partially filled with the liquid and there is a free surface.

Streamlines

- **Streamlines:** It is useful to visualize the flow pattern. Lines joining points of equal velocity - velocity contours - can be drawn. These lines are know as streamlines.
- Here are 2-D streamlines around a cross-section of an aircraft wing shaped body:



- Fluid flowing past a solid boundary does not flow into or out of the solid surface.
- Very close to a boundary wall the flow direction must be along the boundary.

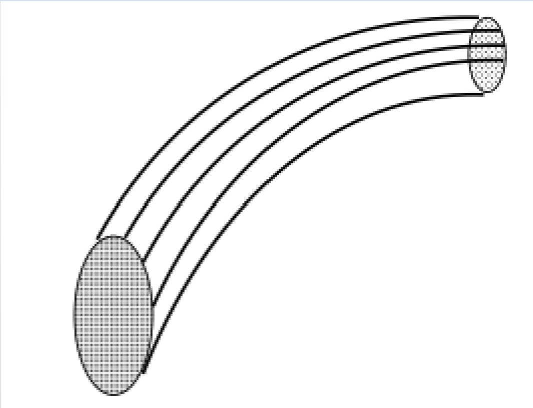
Streamlines

Some points about streamlines:

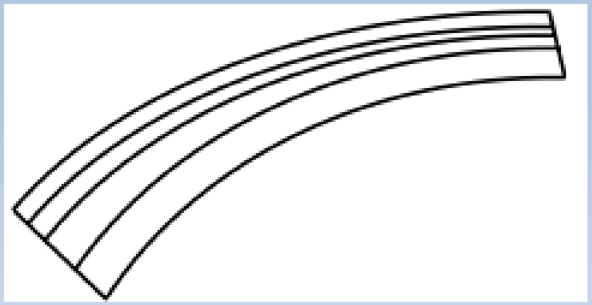
1. Close to a solid boundary, streamlines are parallel to that boundary
2. The direction of the streamline is the direction of the fluid velocity
3. Fluid can not cross a streamline
4. Streamlines can not cross each other
5. Any particles starting on one streamline will stay on that same streamline
6. In unsteady flow streamlines can change position with time
7. In steady flow, the position of streamlines does not change.

Streamtubes

- A circle of points in a flowing fluid each has a streamline passing through it. These streamlines make a tube-like shape known as a streamtube



- In a two-dimensional flow the streamtube is flat (in the plane of the paper):



Streamtubes

- **Some points about streamtubes**

1. The “walls” of a streamtube are streamlines.
2. Fluid cannot flow across a streamline, so fluid cannot cross a streamtube “wall”.
3. A streamtube is not like a pipe. Its “walls” move with the fluid.
4. In unsteady flow streamtubes can change position with time
5. In steady flow, the position of streamtubes does not change.

Flow rate

- **Mass flow rate**

$$\dot{m} = \frac{dm}{dt} = \frac{\text{mass}}{\text{time taken to accumulate this mass}}$$

- A simple example: An empty bucket weighs 2.0kg. After 7 seconds of collecting water the bucket weighs 8.0kg, then:

$$\begin{aligned}\text{mass flow rate} = \dot{m} &= \frac{\text{mass of fluid in bucket}}{\text{time taken to collect the fluid}} \\ &= \frac{8.0 - 2.0}{7} \\ &= 0.857 kg / s\end{aligned}$$

Flow rate

- Volume flow rate – Discharge: More commonly we use volume flow rate . Also know as discharge. The symbol normally used for discharge is Q.

$$\text{discharge, } Q = \frac{\text{volume of fluid}}{\text{time}}$$

- A simple example: If the bucket above fills with 2.0 litres in 25 seconds, what is the discharge?

$$Q = \frac{2.0 \times 10^{-3}\ m^3}{25 \text{ sec}}$$
$$= 0.0008 m^3 / s$$
$$= 0.8\ l / s$$

Example 1: Water flows through a rubber hose 2 cm in diameter at a velocity of 4 m/s. What must be the diameter of the nozzle in order that the water emerge at 16 m/s?

The area is proportional to the square of diameter, so:

$$v_1 d_1^2 = v_2 d_2^2$$

$$d_2^2 = \frac{v_1 d_1^2}{v_2} = \frac{(4\text{ m/s})(2\text{ cm})^2}{(20\text{ cm})^2}$$

d_2 = 0.894 cm

Example 1 (Cont.): Water flows through a rubber hose 2 cm in diameter at a velocity of 4 m/s. What is the rate of flow in m³/min?

$$R = v_1 A_1 = v_2 A_2$$

$$R = v_1 A_1; \quad A_1 = \frac{\pi d_1^2}{4}$$

$$R_1 = v_1 \frac{\pi d_1^2}{4} = \frac{(4 \text{ m/s})\pi(0.02 \text{ m})^2}{4}$$

***R_1* = 0.00126 m³/s**

$$R_1 = 0.00126 \frac{\text{m}^3}{\text{min}}\left(\frac{1 \text{ min}}{60 \text{ s}}\right)$$

$R_1 = 0.0754$ m³/min