What we know about Fluid Mechanics

Image from: www.axs.com

1.
2.
3.
4.
5.
6.

What we know about Fluid Mechanics

1. MEB (single input, single output, steady, incompressible, no rxn, no phase change, little heat; good for pipes, pumps; Moody chart; Fanning friction factor versus Re)

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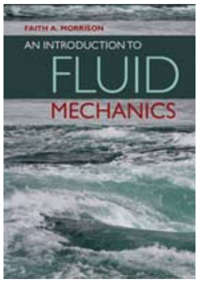
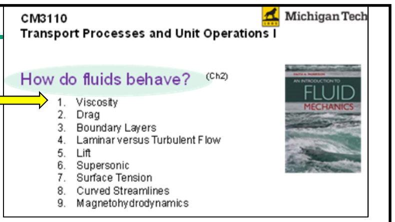
How do fluids behave? (Ch2)

1. Viscosity
2. Drag
3. Boundary Layers
4. Laminar versus Turbulent Flow
5. Lift
6. Supersonic
7. Surface Tension
8. Curved Streamlines
9. Magnetohydrodynamics



www.chem.mtu.edu/~fmorriso/cm310/cm310.html

How do Fluids Behave?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1. Viscosity, μ

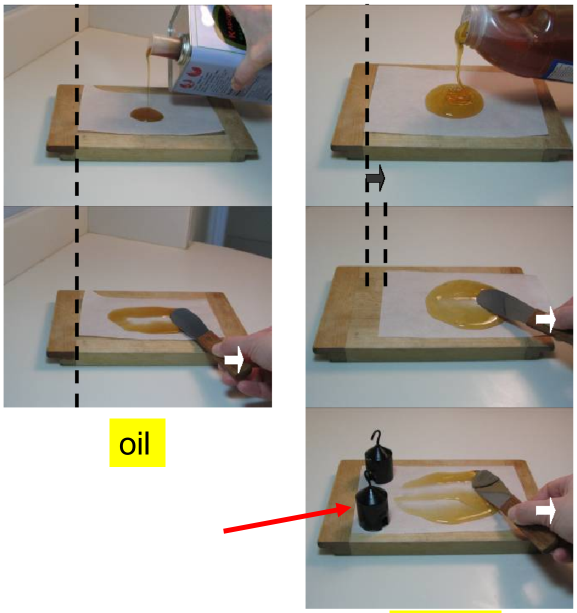
A measure of a liquid's resistance to flow

water
(modest viscosity)

honey
(high viscosity)

How do Fluids Behave?

Viscous fluids transmit stress from one location to another.



oil

honey

How do Fluids Behave?

Momentum Flux

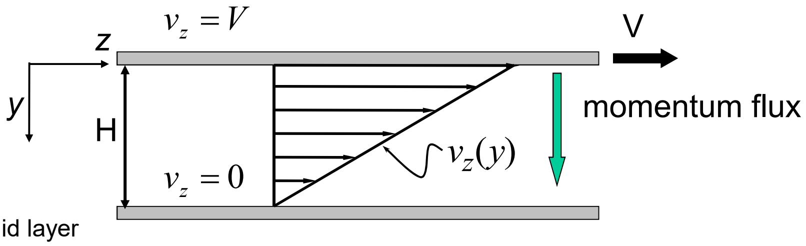
Momentum ($\mathfrak{p}$) = mass * velocity

$$\boxed{\underline{\mathfrak{p}} = m\underline{v}}$$

vectors

Viscosity determines the magnitude of momentum flux

top plate has momentum, and it transfers this momentum to the top layer of fluid



$v_z = V$

z

V

y

H

momentum flux

$v_z(y)$

$v_z = 0$

Each fluid layer transfers the momentum downward

How do Fluids Behave?

How is force-to-move-plate related to *V*?

$$\frac{F}{A} = +\mu \frac{V}{H} = \mu \left(\frac{v_z\big|_{y=0} - v_z\big|_{y=H}}{H-0} \right)$$

(Note choice of coordinate system)

Stress on a *y*-surface in the *z*-direction

$$= -\mu \left(\frac{\Delta v_z}{\Delta y} \right)$$

$$\boxed{\tilde{\tau}_{yz} = \mu \left(\frac{dv_z}{dy} \right)}$$

Newton's Law of Viscosity

(See discussion of sign convention of stress; we use the tension-positive convention)

$$-\tilde{\tau}_{yz} = \frac{F}{A}$$

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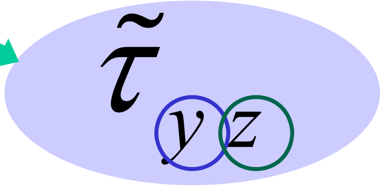
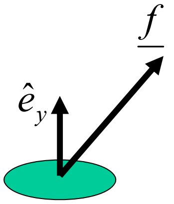
$$\tilde{\tau}_{yz} = \frac{force}{area} = \frac{kg\ m/s^2}{area} = \frac{(kg)(m/s)}{(s)(area)}$$

Momentum Flux

9 stress coefficients at a point in a fluid



Why 9? 3-d space, vector velocity. It takes 9 components to describe stress



$$\underline{f} = A(\tau_{yx}\hat{e}_x + \tau_{yy}\hat{e}_y + \tau_{yz}\hat{e}_z)$$

stress on a *y*-surface → in the *z*-direction

A surface whose unit normal is in the y-direction

$-\tilde{\tau}_{yz} =$

in the *y*-direction ← flux of *z*-momentum

(See discussion of sign convention of stress; we use the tension-positive convention)

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How do Fluids Behave?

(p110)

Example 2.1: What are the units of viscosity?

$$\tilde{\tau}_{yz} = \mu\left(\frac{dv_z}{dy}\right)$$

Newton's Law of Viscosity

Viscosity, Greek letter "mu"

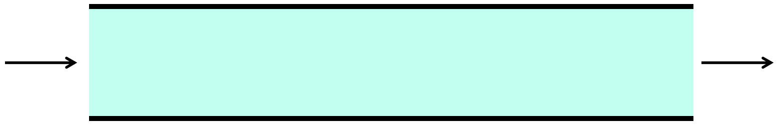
How do Fluids Behave?

Viscosity

A measure of a liquid's resistance to flow

Viscous fluids transmit stress from one location to another.

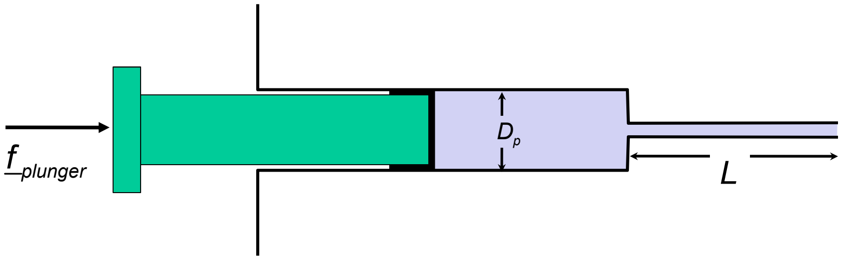
Viscosity is responsible for the development of pressure distributions in laminar flow.



How do Fluids Behave?

(See text, p110)

Example 2.2: How much force does it take to inject a water-like solution through a 16-gauge needle (inner diameter=1.194 mm, L=40mm)?



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How do Fluids Behave?

Need to know: $\Delta p(Q)$

From the methods of this course, we shall see that for Newtonian fluids:

Hagen-Poiseuille equation
(slow flow through tubes)

$$\boxed{Q = \frac{\pi(p_0 - p_L)R^4}{8\mu L}}$$

14

How do Fluids Behave?

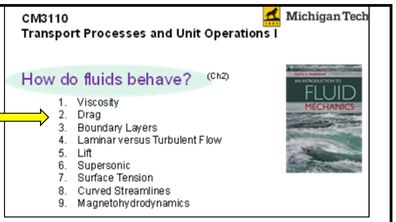
$$\underbrace{\sum_{all\ \ forces} \underline{f}}_{\textbf{Forces}\text{ (including viscous forces)}} \underbrace{= m\underline{a} = \text{Rate of change of momentum}}_{\textbf{Inertia}}$$

In the momentum balance, viscosity appears because it produces a force:

---

2. Drag F_{drag}

The <u>retarding</u> force on an object due to a fluid (*retarding* implies opposite in direction to the fluid velocity)



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How do fluids behave? (Ch2)

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2. Drag F_{drag}

Image from: www.g4tv.com

The retarding force on an object due to a fluid (*retarding* implies opposite in direction to the fluid velocity)

Drag is a consequence of *viscosity*

We study how to:

Calculate drag,

1. Calculate velocity
2. Calculate force on the object surface
3. Calculate the component of that force in the direction of the flow

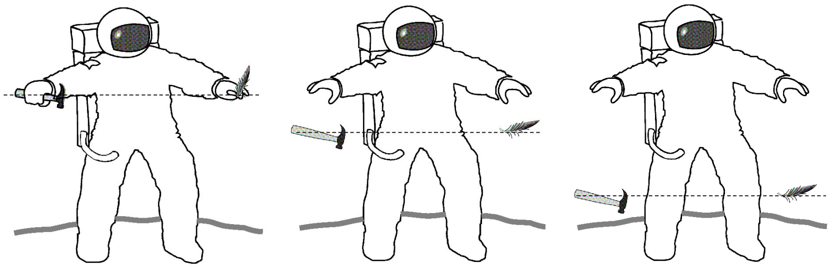
} Microscopic-momentum balance

When impossible to calculate,

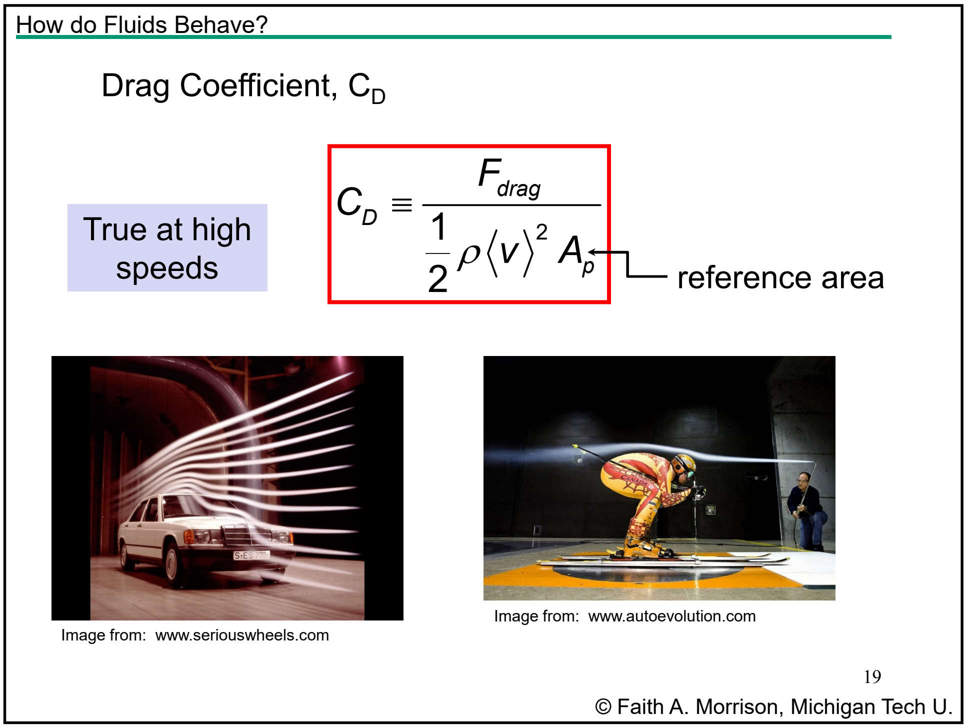
1. Measure force on model in a wind/water tunnel
2. Correlate using dimensional analysis
3. Scale up to system of interest

How do Fluids Behave?

Without drag, objects of different weights, shapes, fall at the same speed:



In 1971, astronaut David Scott conducted Galileo's experiment on the moon as part of Apollo 15.



How do Fluids Behave?

Drag Coefficient, C_D

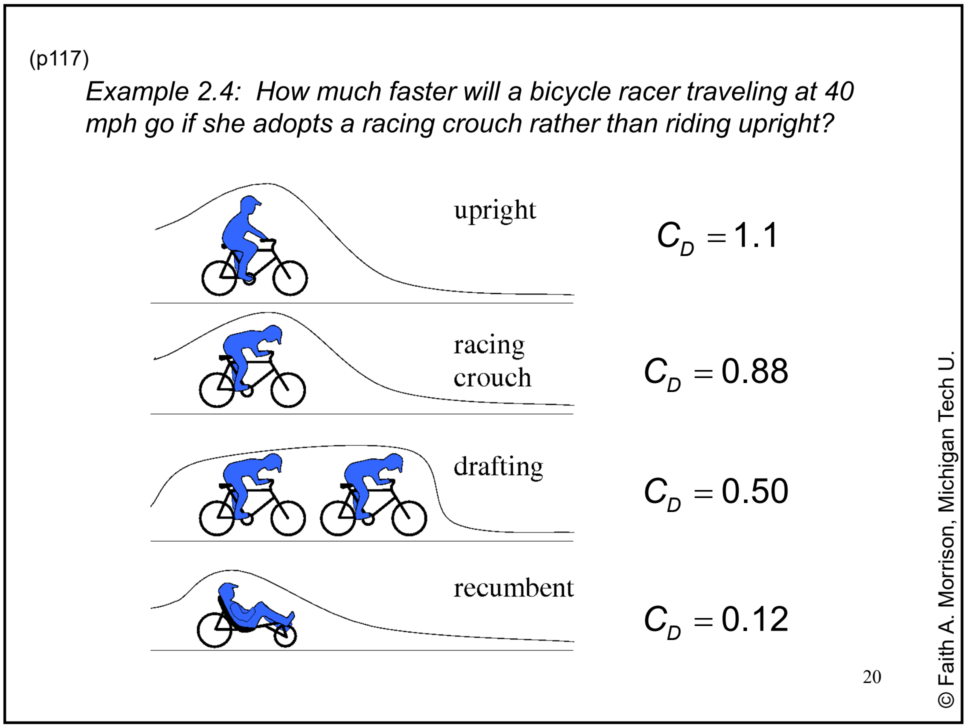
True at high speeds

$$\boxed{C_D \equiv \frac{F_{drag}}{\frac{1}{2}\rho\langle v\rangle^2 A_p}}$$

reference area

Image from: www.seriouswheels.com

Image from: www.autoevolution.com



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Example 2.4: How much faster will a bicycle racer traveling at 40 mph go if she adopts a racing crouch rather than riding upright?

upright	$C_D = 1.1$
racing crouch	$C_D = 0.88$
drafting	$C_D = 0.50$
recumbent	$C_D = 0.12$

How do Fluids Behave?

Under what conditions is drag a simple matter of knowing C_D?

Could vary with:
- Flow speed
- Shape
- Density
- Viscosity
- Temperature
- . . .

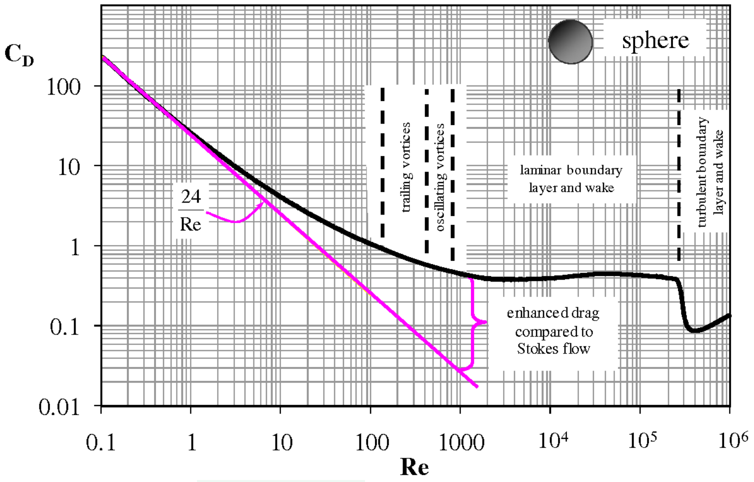
$$C_D \equiv \frac{F_{drag}}{\frac{1}{2}\rho\langle v\rangle^2 A_p}$$

(i.e., Why is this so?
When is this so?)

How do Fluids Behave?

Drag behavior of a sphere

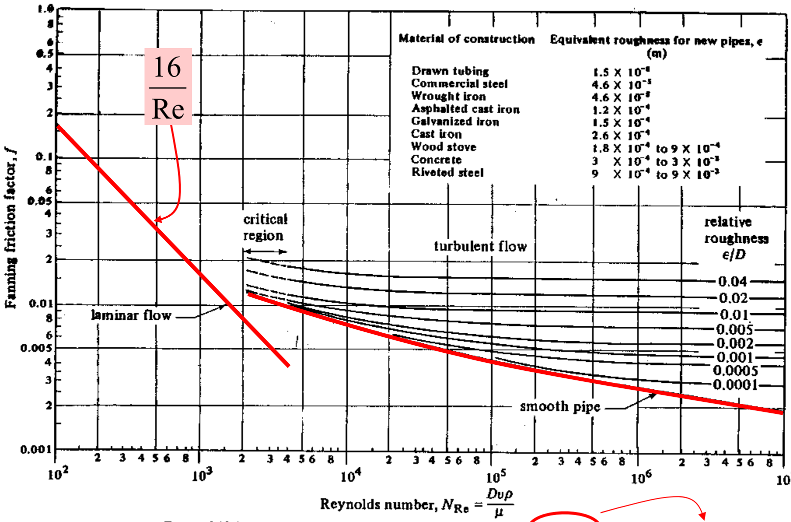
(Similar to using the Moody Chart when interested in wall drag in pipes)



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

Moody Chart: Data Correlation for Friction in Straight Pipes

(Review)



Material of construction	Equivalent roughness for new pipes, ε (m)
Drawn tubing	1.5×10^{-6}
Commercial steel	4.6×10^{-5}
Wrought iron	4.6×10^{-5}
Asphalted cast iron	1.2×10^{-4}
Galvanized iron	1.5×10^{-4}
Cast iron	2.6×10^{-4}
Wood stove	1.8×10^{-4} to 9×10^{-4}
Concrete	3×10^{-4} to 3×10^{-3}
Riveted steel	9×10^{-4} to 9×10^{-3}

$$\frac{16}{Re}$$

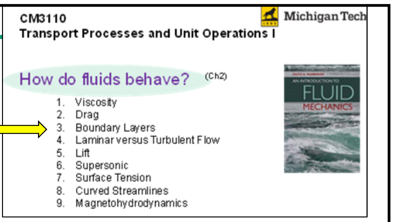
FIGURE 2.10-3. *Friction factors for fluids inside pipes. [Based on L. F. Moody, Trans. A.S.M.E., 66, 671, (1944); Mech. Eng. 69, 1005 (1947). With permission.]*

Moody Chart

(image from: Geankoplis)

How do Fluids Behave?

3. Boundary Layers (BL)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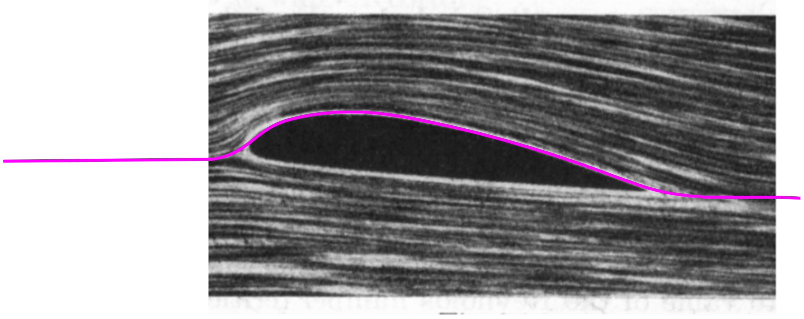
- Regions near solid surfaces in which viscosity dominates the flow behavior, especially at high speeds

How do Fluids Behave?

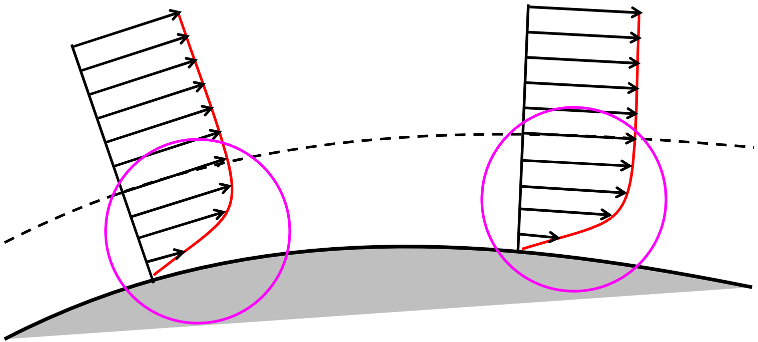
2.3 Boundary Layers (BL)

BL form at high speeds

- Regions near solid surfaces in which viscosity dominates the flow behavior, especially at high speeds



How do Fluids Behave?



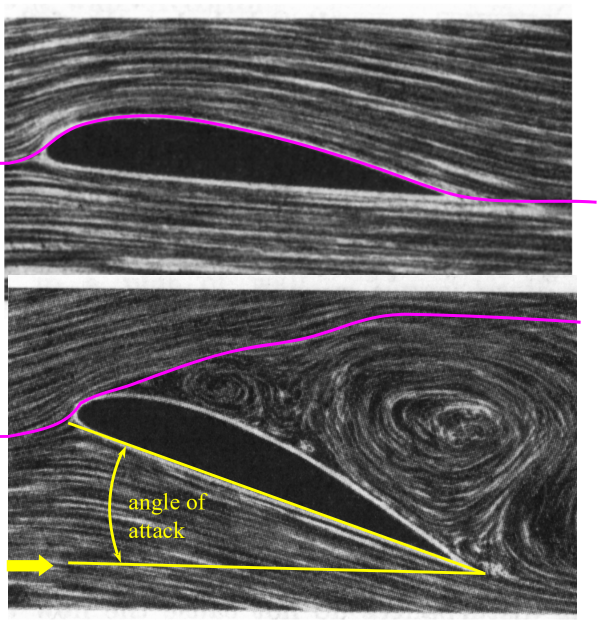
There is relative motion near the surfaces (viscosity is important);

Away from surfaces, the flow is uniform (viscosity is not important; inertia dominates)

Newton's Law of Viscosity

$$\tilde{\tau}_{yz} = \mu\left(\frac{dv_z}{dy}\right)$$

How do Fluids Behave?



Attached boundary layer near surface

Boundary layer detaches

Source: *Illustrated experiments in fluid mechanics: the NCFMF book of film notes*, MIT Press, 1972

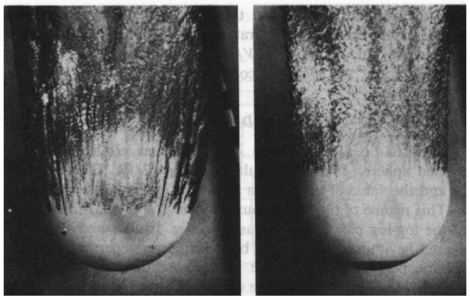
How do Fluids Behave?

Why is the surface of a golf ball designed the way it is?

How do Fluids Behave?

Manipulate boundary-layer separation

When the boundary layer is turbulent, it detaches farther back (yielding lower drag)



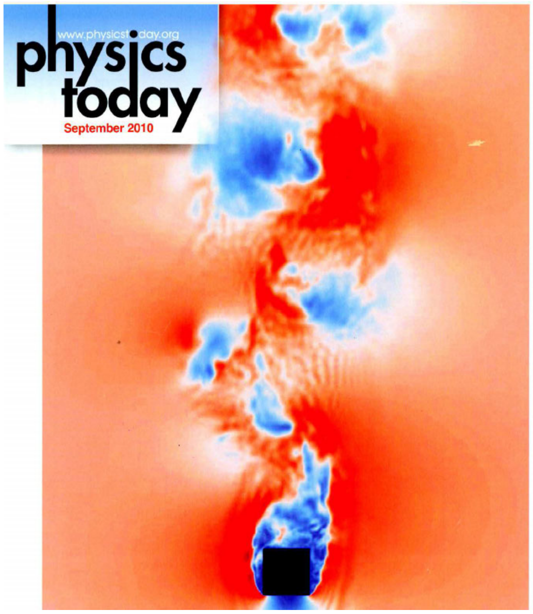
smooth ball

rough ball

H. Schlichting, Boundary Layer Theory (McGraw-Hill, NY 1955.

---

cover: This image from a simulation of wind blowing past a building (black square) reveals the vortices that are shed downwind of the building; dark orange represents the highest air speeds, dark blue the lowest. As a result of such vortex formation and shedding, tall buildings can experience large, potentially catastrophic forces. (Courtesy of the computational fluid dynamics group at Rowan William Davies and Irwin Inc.)



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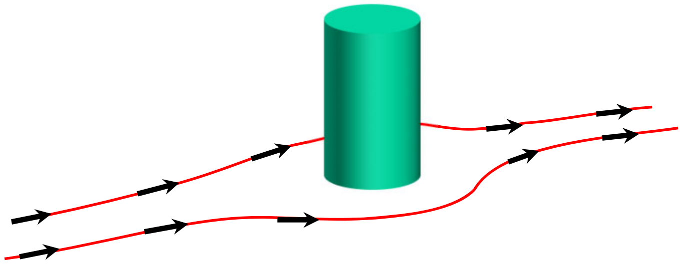
Example 2.5: A new tower hotel, cylindrical in shape and 100 ft in diameter, has been built in a resort town near the sea on the windward side of an island. Hotel guests complain that there are often uncomfortably high winds near several of the entrances to the tower. How do the wind speed and pressure vary with position around the tower and with on-shore wind speed?



Boundary Layers

- •The full Navier-Stokes is **hard** to solve; when viscosity is zero, however, it's **easy to solve the N-S for $\underline{v}$ and p**

- •Viscosity is NOT zero; *however*, outside the boundary layer, viscosity is not important.

- •STRATEGY: When away from surfaces, solve for outer (viscosity=0) flow

For inviscid flows:
•$\underline{v}$ comes from stream function, ψ; (Diff Eqns)
•Pressure comes from $\underline{v}$ and the Bernoulli equation:

Bernoulli equation

$$\left(\frac{p}{\rho}+\frac{\langle v\rangle^2}{2}+z\right)=\textit{constant along a streamline}$$

(see section 8.2 of our text)

Boundary Layers

Velocity outside boundary layer

cylinder in uniform flow:

(potential flow solution)

$$\underline{v} = \begin{pmatrix} U\left(1-\frac{R^2}{r^2}\right)\cos\theta \\ -U\left(1+\frac{R^2}{r^2}\right)\sin\theta \\ 0 \end{pmatrix}_{r\theta z}$$

Pressure outside boundary layer

Bernoulli equation

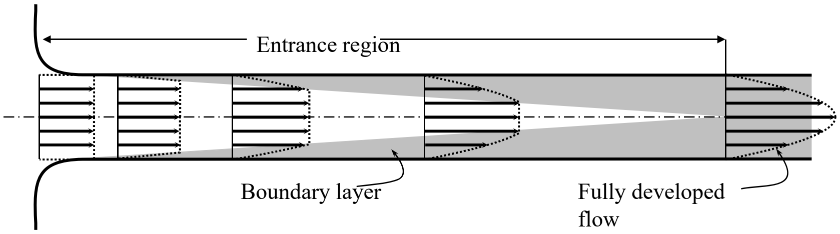
$$\left(\frac{p}{\rho}+\frac{v^2}{2}+z\right) = \textit{constant along a streamline}$$

(see section 8.2 of our text)

How do Fluids Behave?

Boundary Layers in Internal Flow:

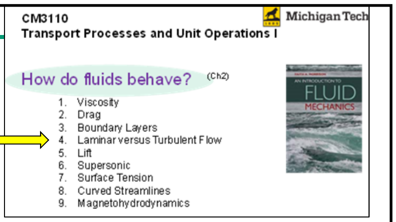
Entrance flow field in pipe flow



(see section 8.2 of our text)

How do Fluids Behave?

4. Laminar versus Turbulent Flow



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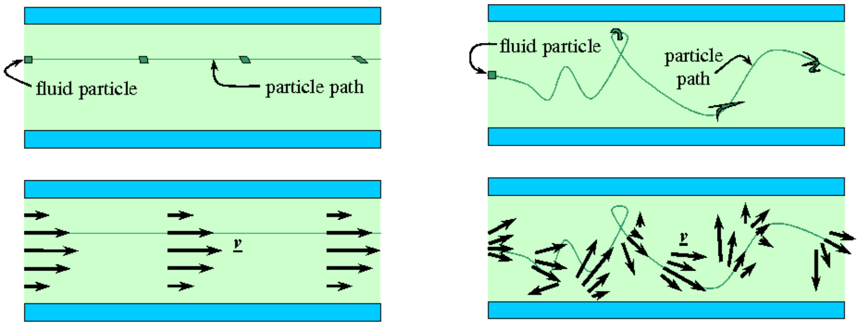
How do Fluids Behave?

4. Laminar versus Turbulent Flow



a) Laminar flow

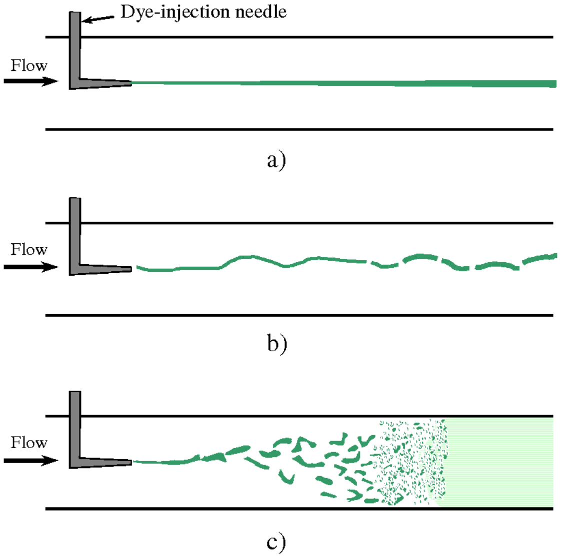
b) Turbulent flow

Viscosity dominates

Inertia dominates

How do Fluids Behave?

Reynolds' Experiment



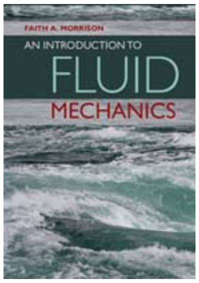
Viscosity dominates

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

Inertia dominates

How do *fluids* behave?

(Ch2)



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AN INTRODUCTION TO

FLUID MECHANICS

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2. Drag
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Advanced

www.chem.mtu.edu/~fmorriso/cm310/cm310.html

Take-Away from Today:

How do fluids behave?

How do Fluids Behave?

1. Viscosity $$\tilde{\tau}_{yz} = \mu \left(\frac{dv_z}{dy} \right)$$
2. Drag $$C_D \equiv \frac{F_{drag}}{\frac{1}{2}\rho \langle v \rangle^2 A_p}$$
3. Boundary Layers

   Viscous effects within BL; no viscous effects in main stream; Bernoulli equation (like MEB) assumes no viscous effects

   (outside the boundary layer) $$\left(\frac{p}{\rho} + \frac{v^2}{2} + z \right) = \textit{constant along a streamline}$$
4. Laminar versus Turbulent Flow

   (we know about this already, $f(\mathrm{Re})$)

Take-Away from Today:

How do fluids behave?

How do Fluids Behave?

Viscous stress $\tilde{\tau}$

1. Viscosity $$\tilde{\tau}_{yz} = \mu \left(\frac{dv_z}{dy} \right)$$
2. Drag $$C_D \equiv \frac{F_{drag}}{\frac{1}{2}\rho \langle v \rangle^2 A_p}$$

Viscous effects dominate near walls

3. Boundary Layers

   Viscous effects within BL; no viscous effects in main stream; Bernoulli equation (like MEB) assumes no viscous effects

   (outside the boundary layer) $$\left(\frac{p}{\rho} + \frac{v^2}{2} + z \right) = \textit{constant along a streamline}$$

Inertial effects dominate away from walls

4. Laminar versus Turbulent Flow

   (we know about this already, $f(\mathrm{Re})$)

What we know about Fluid Mechanics

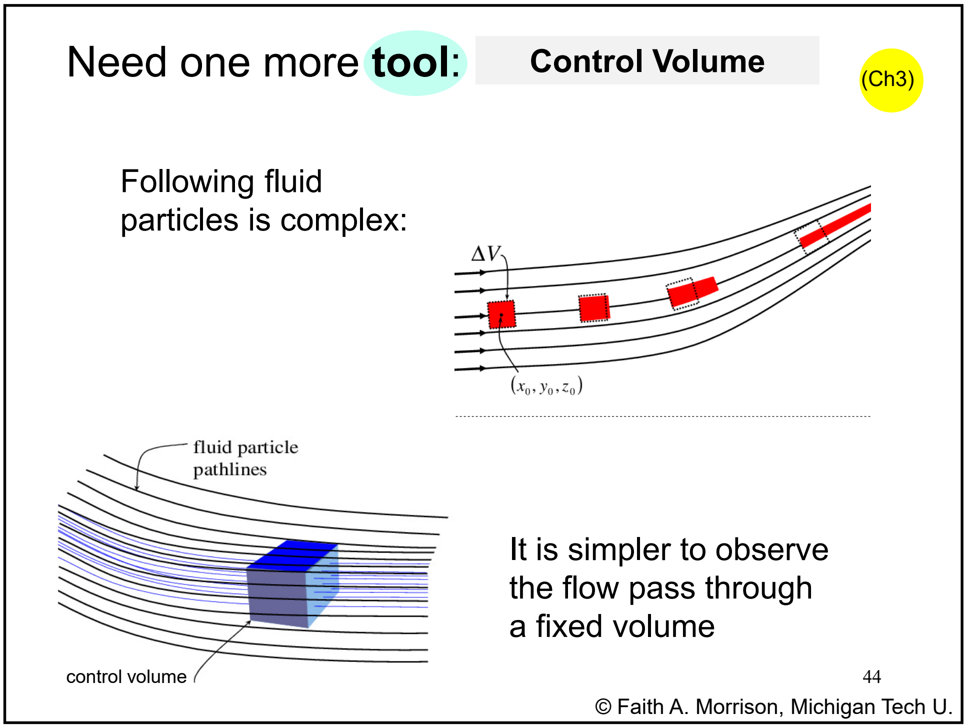
1. MEB (single input, single output, steady, incompressible, no rxn, no phase change, little heat; good for pipes, pumps; Moody chart; Fanning friction factor versus Re)
2. Fluid Statics ($p_{bot} = p_{top} + \rho g h$); same elevation, same pressure; good for manometers, water in tanks)
3. Math is in our future
4.
5.
6.

What we know about Fluid Mechanics

1. MEB (single input, single output, steady, incompressible, no rxn, no phase change, little heat; good for pipes, pumps; Moody chart; Fanning friction factor versus Re)
2. Fluid Statics ($p_{bot} = p_{top} + \rho g h$); same elevation, same pressure; good for manometers, water in tanks)
3. **Newton's Law of Viscosity** (fluids transmit forces through momentum flux)
4. **Momentum flux** (=stress) has 9 components
5. **Drag** is a consequence of viscosity
6. **Boundary layers form** (viscous effects are confined near surfaces at high speeds)

What we know about Fluid Mechanics

8. **Sometimes viscous effects dominate; sometimes inertial effects dominate**



Need one more **tool**: **Control Volume**

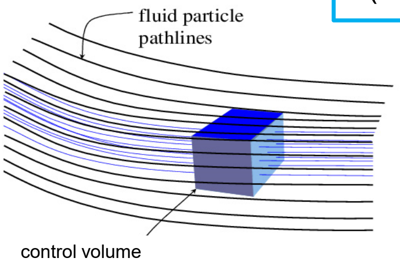
(Ch3)

Following fluid particles is complex:

It is simpler to observe the flow pass through a fixed volume

Control Volume

A chosen volume in a flow on which we perform balances (mass, momentum, energy)



- Shape, size are arbitrary; choose to be convenient

- Because we are now balancing on *control volumes* instead of on *bodies*, the laws of physics are written differently

---

Control Volume

Mass balance, flowing system (open system; control volume):

$$\left\{ \begin{array}{c} net\ mass \\ flowing\ in \end{array} \right\} = \cancel{\left\{ \begin{array}{c} rate\ of \\ accumulation \\ of\ mass \end{array} \right\}}$$

$$\sum_{in} - \sum_{out}$$

steady state

Control Volume

Momentum balance, flowing system (open system; control volume): $\sum_{all\ forces} \underline{f} = m\underline{a} \Rightarrow$

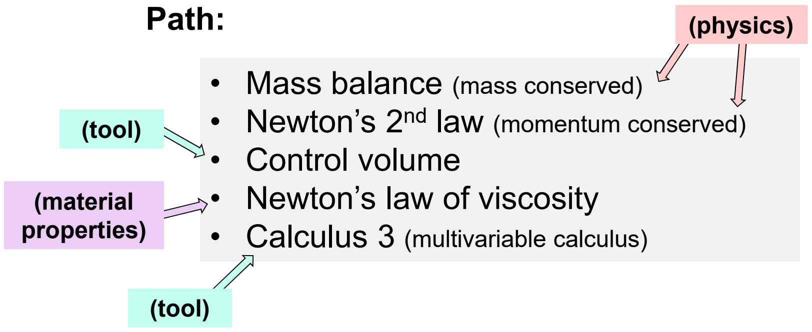
$$\begin{Bmatrix} \text{sum of forces} \\ \text{acting } \underline{\text{on}} \text{ control vol} \end{Bmatrix} + \underset{\sum_{in} - \sum_{out}}{\begin{Bmatrix} \text{net momentum} \\ \text{flowing in} \end{Bmatrix}} = \underset{\text{steady state}}{\begin{Bmatrix} \cancel{\begin{matrix} \text{rate of} \\ \text{accumulation} \\ \text{of momentum} \end{matrix}} \end{Bmatrix}}$$

$$\sum_i \underline{F}_{on_i} + \sum_i \begin{Bmatrix} \text{momentum} \\ \text{flowing } \underline{\text{in}} \\ \text{in the streams} \end{Bmatrix} - \sum_i \begin{Bmatrix} \text{momentum} \\ \text{flowing } \underline{\text{out}} \\ \text{in the streams} \end{Bmatrix} = 0$$

note that momentum is a vector quantity

We are ready to try a momentum balance.

Path:



- Mass balance (mass conserved)
- Newton's 2nd law (momentum conserved)
- Control volume
- Newton's law of viscosity
- Calculus 3 (multivariable calculus)

Michigan Tech

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Transport I
Part I: Fluid Mechanics: ***Microscopic Balances***

NEXT

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