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# OREGON STATE UNIVERSITY SCHOOL of CBEE
# DEPARTMENT OF CHEMICAL ENGINEERING

## CHE 331
## Transport Phenomena I
## Non-Newtonian Fluids


## Dr. Goran Jovanovic


Reading Assignment:

1) Liquid Viscosity Correlations for Flowmeter Calculations; Roger Gilmont
2) Non-Newtonian Flow I - Characterization of Fluid Behavior; Boger D.V and Halmos A.

**Please turn-off cell phones**

# CLASSIFICATION OF FLUIDS

Fluids give and flow under stress. Newtonians are the simplest of fluids, and they are characterized by the following property:

*The velocity gradient (Shear Rate) at a point within the fluid flow field is proportional to the Shear Stress at that point.*

$$Shear\ \ rate \propto Shear\ \ sterss$$

$$\frac{du}{dy} \propto \tau$$

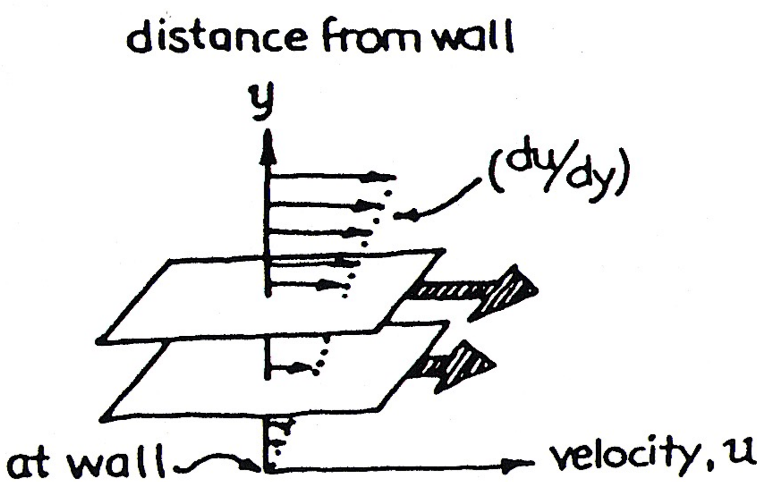
$$\tau_{xy} = \mu\left(\left|\frac{du_x}{dy}\right|\right)$$

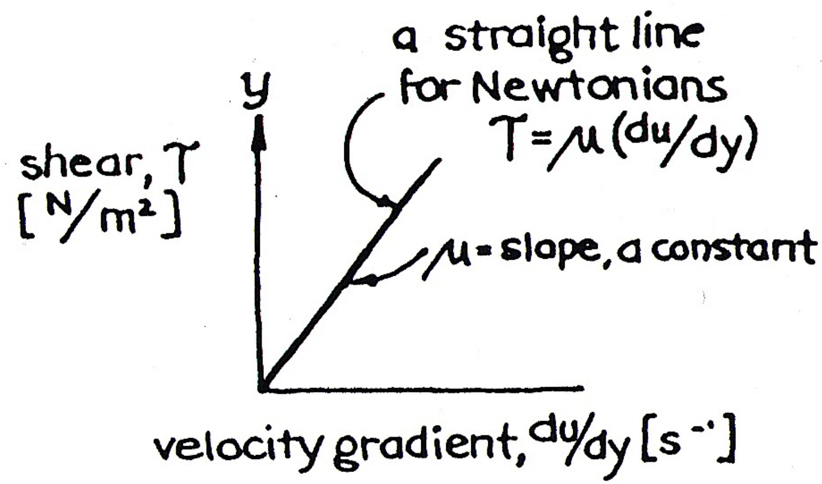
Newton's Law

$$\tau_{xy} = -\mu\left(\frac{d\vec{u}_x}{dy}\right)$$

*All other fluids whose Shear rate – Shear stress relationship cannot be described by the above equation are non-Newtonian Fluids!!*

# CLASSIFICATION OF FLUIDS



# CLASSIFICATION OF FLUIDS

**Newtonian Fluids**
Air
Water
Steam
Almost all Gases
Fluids of simple molecules

**Non-Newtonian Fluids**
Suspensions
Slurries
Emulsions
Polymer Solutions
Paints
Biological Fluids
Concrete Mix
. . . . .

**Time Independent**

$$\begin{pmatrix} Shear \\ Rate \end{pmatrix} = f\begin{pmatrix} Shear \\ Stress \\ alone \end{pmatrix}$$

**Time Dependent**
(non elastic)

$$\begin{pmatrix} Shear \\ Rate \end{pmatrix} = f\begin{pmatrix} Shear\ Stress\ + \\ History\ of\ Stress \end{pmatrix}$$

**Viscoelastic**

# CLASSIFICATION OF FLUIDS

How about this fluid:

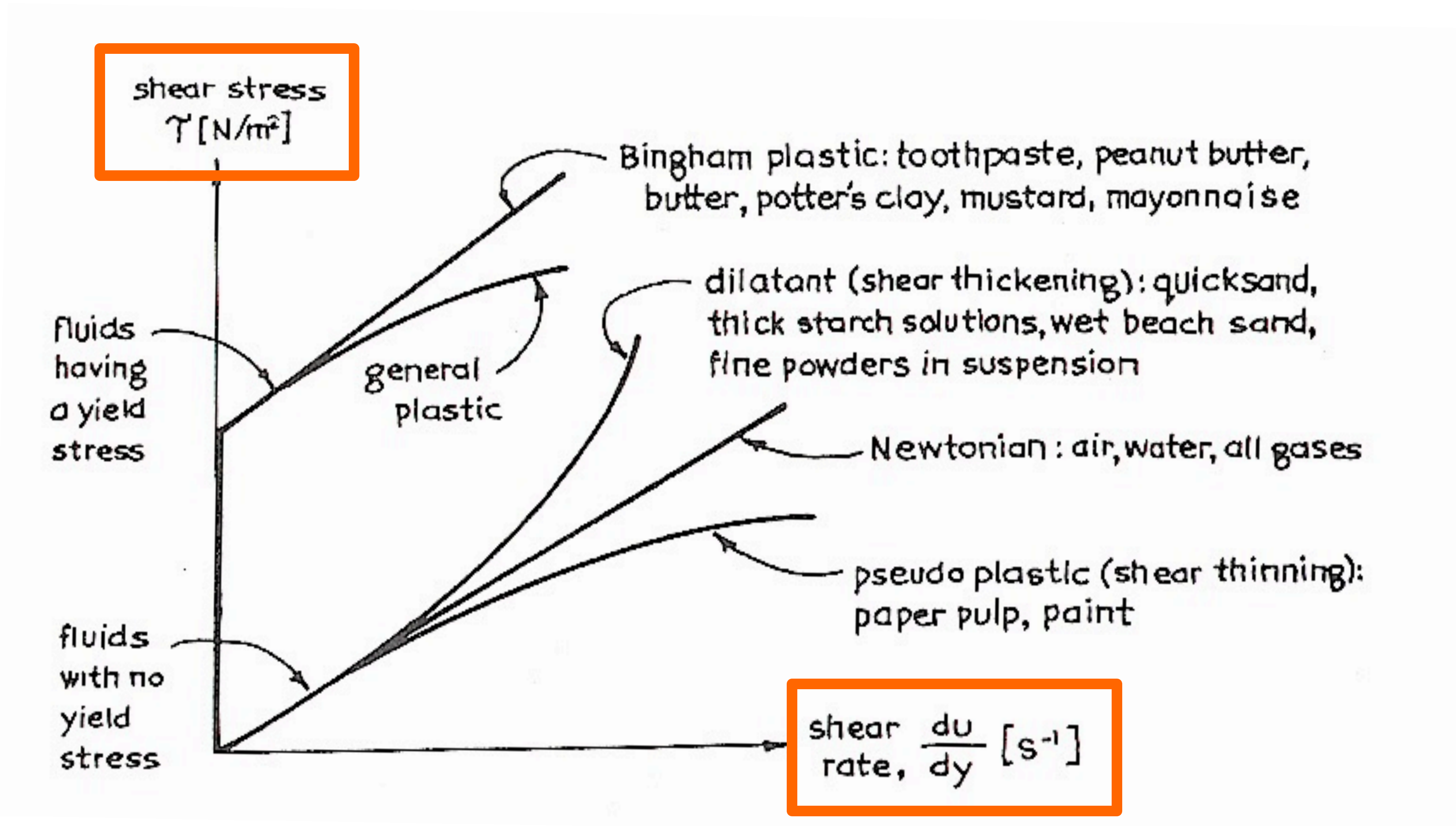
Is it time dependent?

Is it elastic?

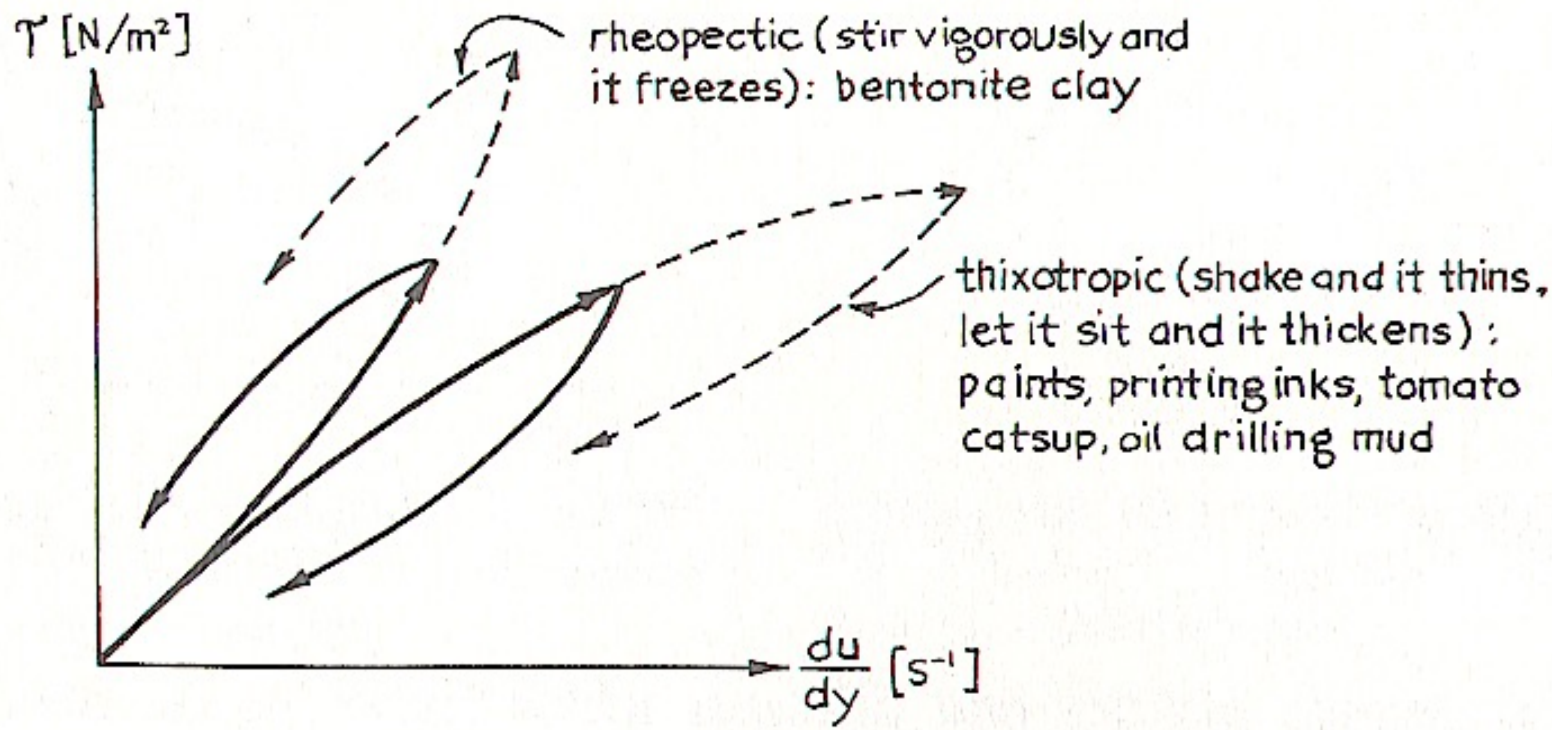
Does it have memory?

So, what kind of fluid this is?

# CLASSIFICATION OF FLUIDS (time independent)



# CLASSIFICATION OF FLUIDS (time dependent viscoelastic)



# CLASSIFICATION OF FLUIDS

**Newtonian Fluids** - The velocity gradient is proportional to the imposed shear stress on fluid. $\Rightarrow$

$$\tau = \mu\left(\left|\frac{du}{dy}\right|\right)$$

$$\Downarrow$$

**Bingham Plastic Fluids** - The velocity gradient is proportional to the shear stress but these fluids have Initial Yield Stress $\tau_o$ $\Leftarrow$

$$\tau = \tau_o + \eta\left(\left|\frac{du}{dy}\right|\right)$$

$$\Downarrow$$

**Power Law Fluids** - Shear stress Shear rate relationship is not linear. K is not viscosity (shear thickening and shear thinning) $\Leftarrow$

$$\tau = K\left(\left|\frac{du}{dy}\right|\right)^n$$

$$\Downarrow$$

**General Plastic Fluids** $\Leftarrow$

$$\tau = \tau_o + K\left(\left|\frac{du}{dy}\right|\right)^n$$

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# CLASSIFICATION OF FLUIDS - *Average Velocity in Pipe*

**Newtonian Fluids**

$$\tau = \mu\left(\left|\frac{du}{dy}\right|\right)$$

***Average velocity in Pipe***

$$u_{avg} = \frac{d_p^2 \rho \sum F}{32\mu L}$$

**Bingham Plastic Fluids**

$$\tau = \tau_o + \eta\left(\left|\frac{du}{dy}\right|\right)$$

$$u_{avg} = \frac{d_p^2 \rho \sum F}{32\eta L}\left(1 - \frac{4}{3}m + \frac{1}{3}m^4\right)$$

$$\text{where } m = \frac{4\tau_o L}{\rho d_p \sum F} = \frac{\tau_o}{\tau_w} \quad \text{and} \quad m \le 1$$

$$\text{if } \tau_o \ge \tau_w \text{ or } m \ge 1 \text{ or } \frac{4\tau_o L}{d_p} \ge \rho \sum F \text{ the flow is frozen}$$

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## Average velocity in Pipe

**Power Law Fluids**

$$\tau = K\left(\left|\frac{du}{dy}\right|\right)^{n}$$

$$u_{avg} = \frac{d_p^2\rho\sum F}{32K\cdot L}\frac{4n}{1+3n}\left(\frac{d_p\rho\sum F}{4K\cdot L}\right)^{\frac{(1-n)}{n}}$$

**General Plastic Fluids**

$$\tau = \tau_o + K\left(\left|\frac{du}{dy}\right|\right)^{n}$$

$$u_{avg} = \frac{d_p^2\rho\sum F}{32K\cdot L}\left(\frac{d_p\rho\sum F}{4K\cdot L}\right)^{\frac{(1-n)}{n}} \times$$

$$\times\ 4n(1-m)^{\frac{(n+1)}{n}}\left(\frac{(1-m)^2}{1+3n}+\frac{2m(1-m)}{1+2n}+\frac{m^2}{1+n}\right)$$

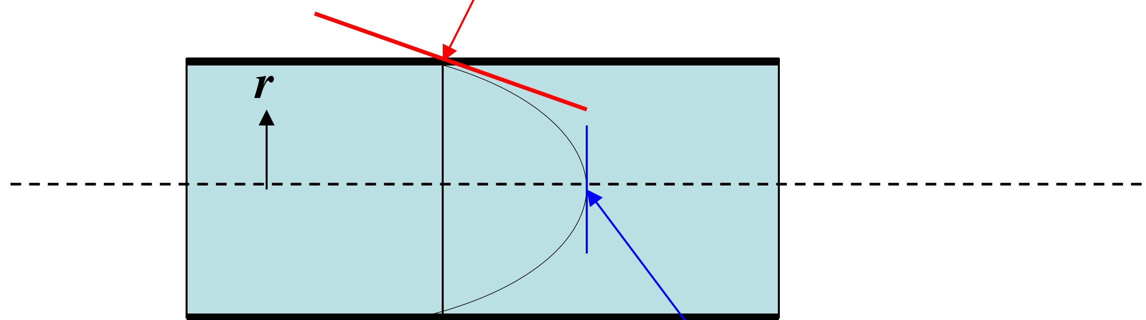
where $m = \dfrac{4\tau_o L}{\rho d_p\sum F} = \dfrac{\tau_o}{\tau_w}$ and $m \le 1$

if $\tau_o \ge \tau_w$ or $m \ge 1$ or $\dfrac{4\tau_o L}{d_p} \ge \rho\sum F$ the flow is frozen

# CLASSIFICATION OF FLUIDS - *Velocity Distribution in Pipe*

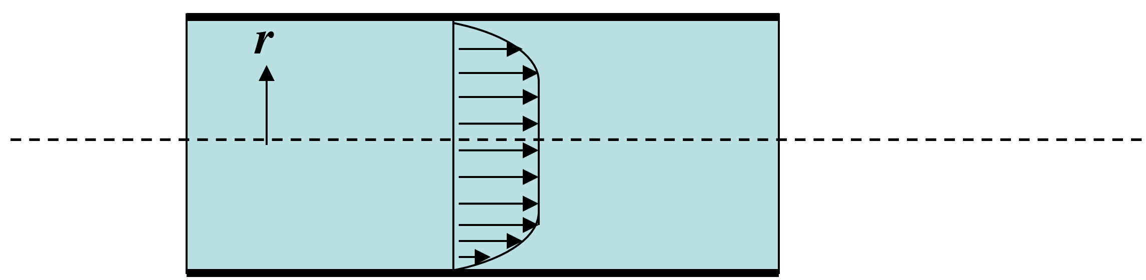
## Newtonian Fluid
## Laminar Flow

$$\tau_w = \mu\left(\left|\frac{du}{dr}\right|\right)_{r=R}$$



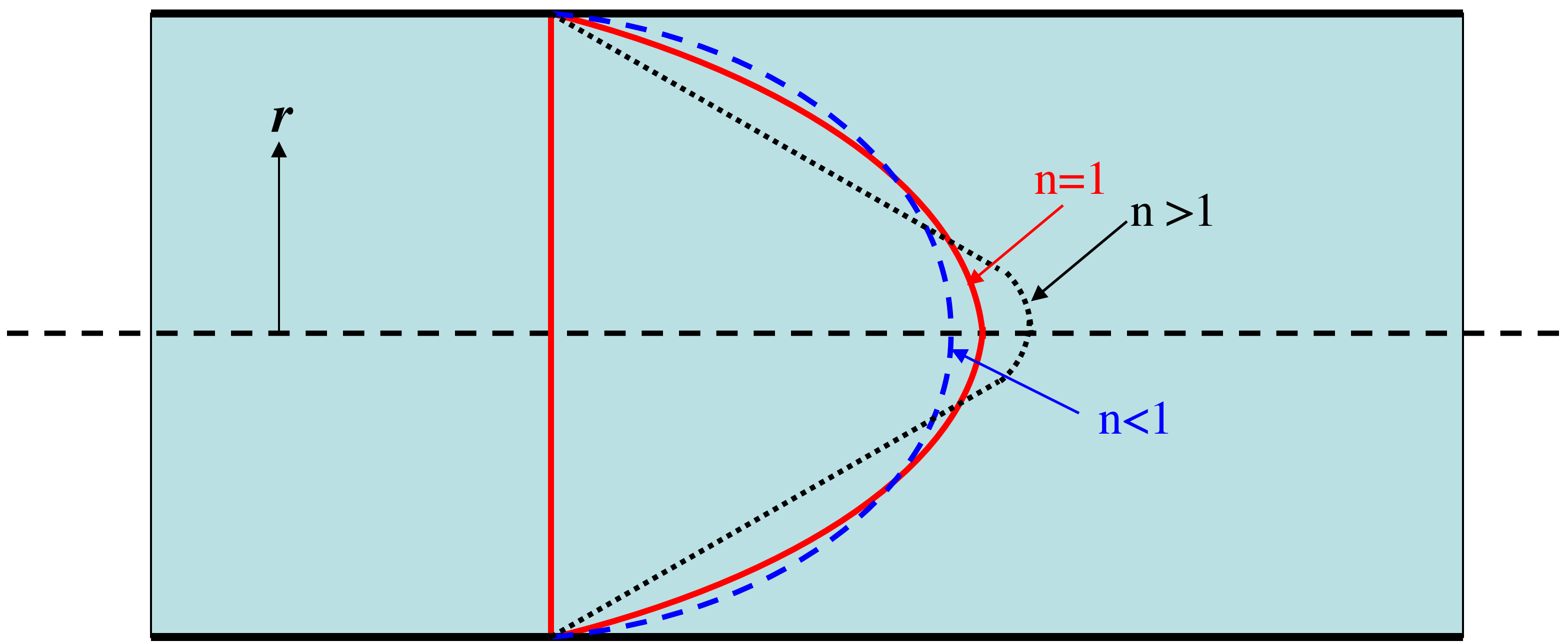

$$\tau_{center} = \mu\left(\left|\frac{du}{dr}\right|\right)_{r=0} = 0$$

## Bingham Plastic Fluid
## Laminar Flow

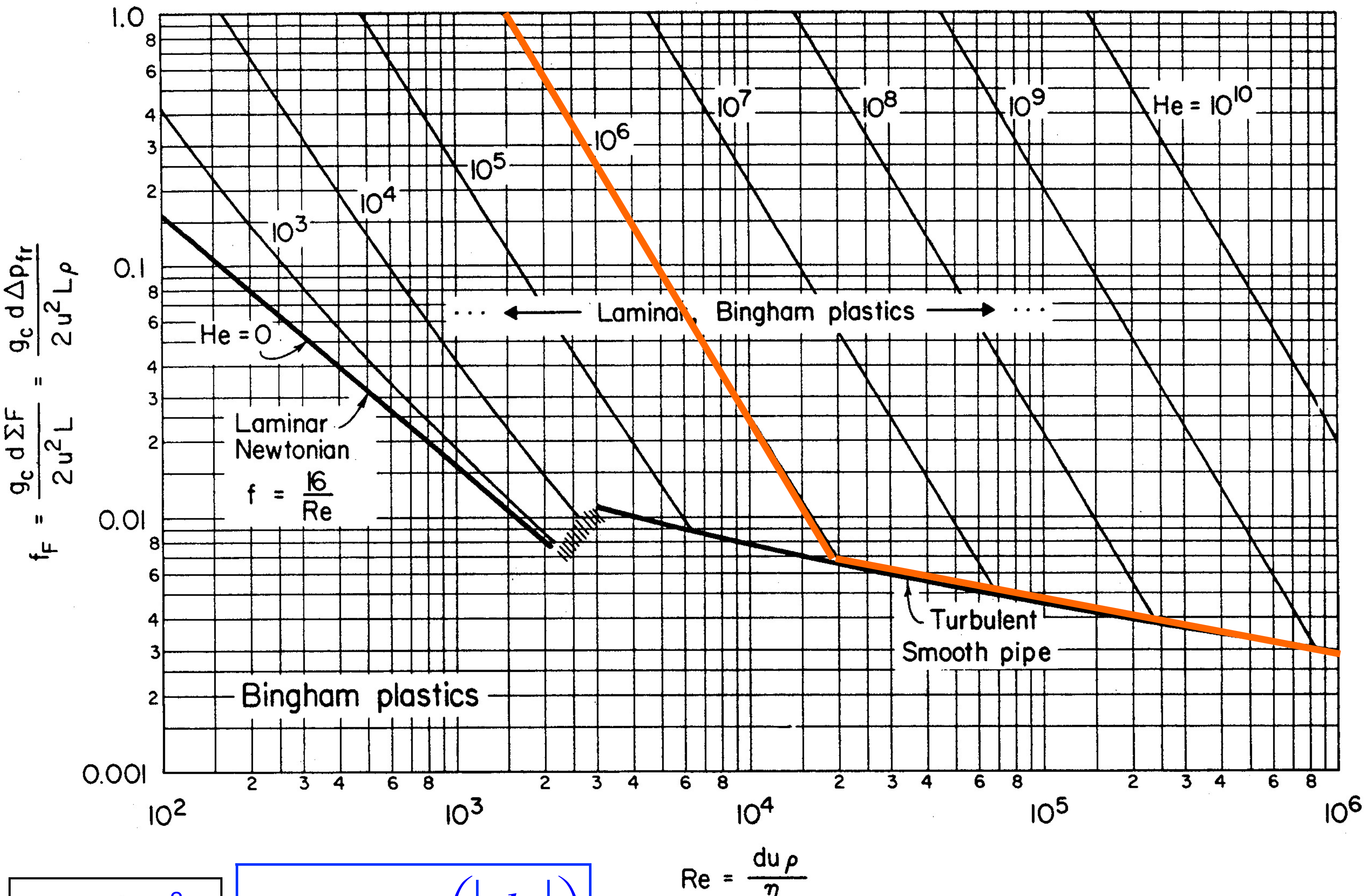


## Power Law Fluid

$$\tau = K\left(\frac{du}{dy}\right)^n$$



# CLASSIFICATION OF FLUIDS – Bingham Plastic - Friction Factor




$$He = \frac{\tau_o d^2 \rho}{\eta^2}$$

$$\tau = \tau_o + \eta\left(\left|\frac{du}{dy}\right|\right)$$

**Example He=1,000,000.**

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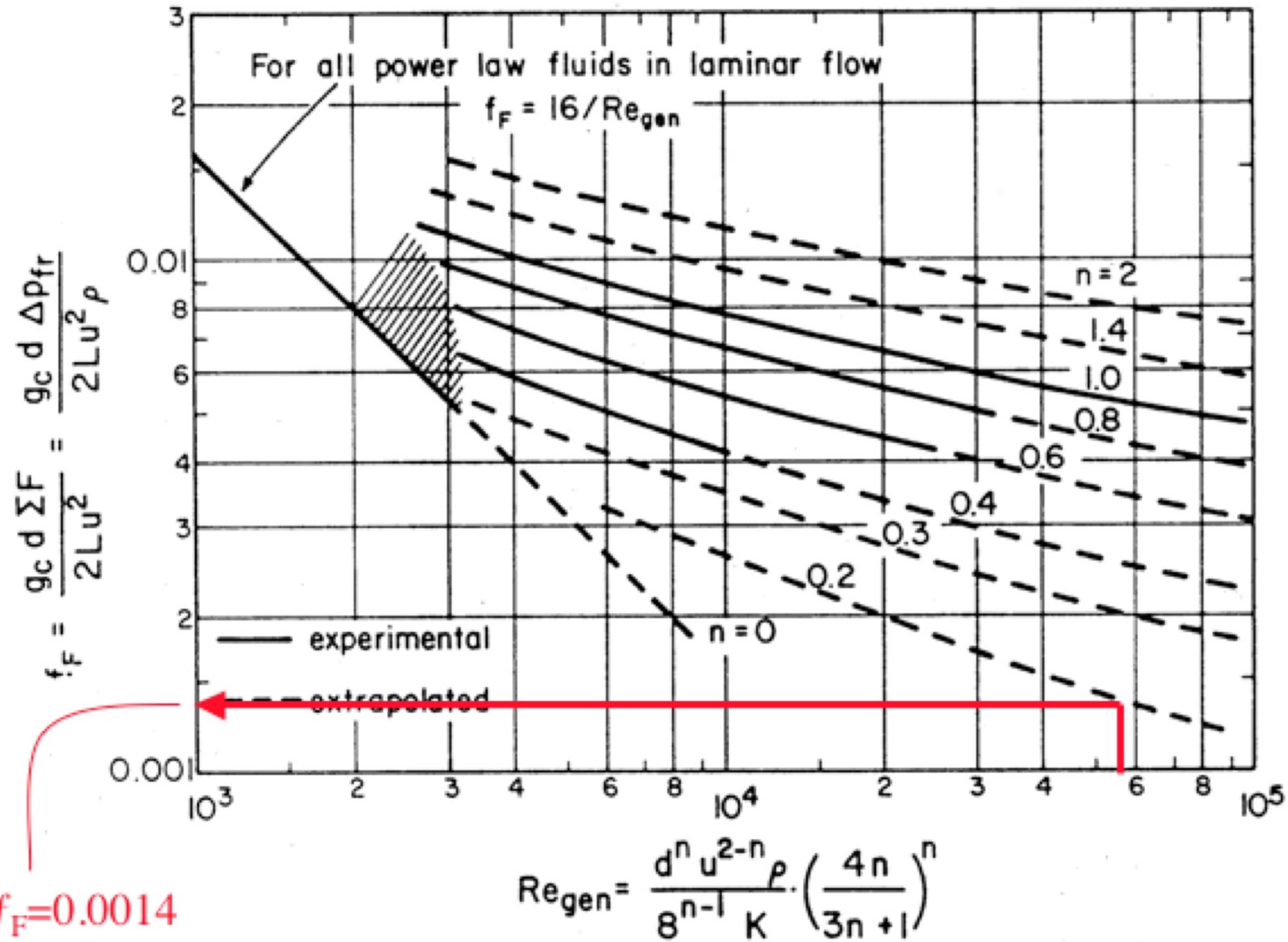
# CLASSIFICATION OF FLUIDS – Power law Fluids Friction Factor




$f_F$=0.0014

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*Thank you for your attention!*