M4
MIXING CONCEPTS

Turbulence

LAMINAR AND TURBULENT MIXING

coffee

paint

Turbulence

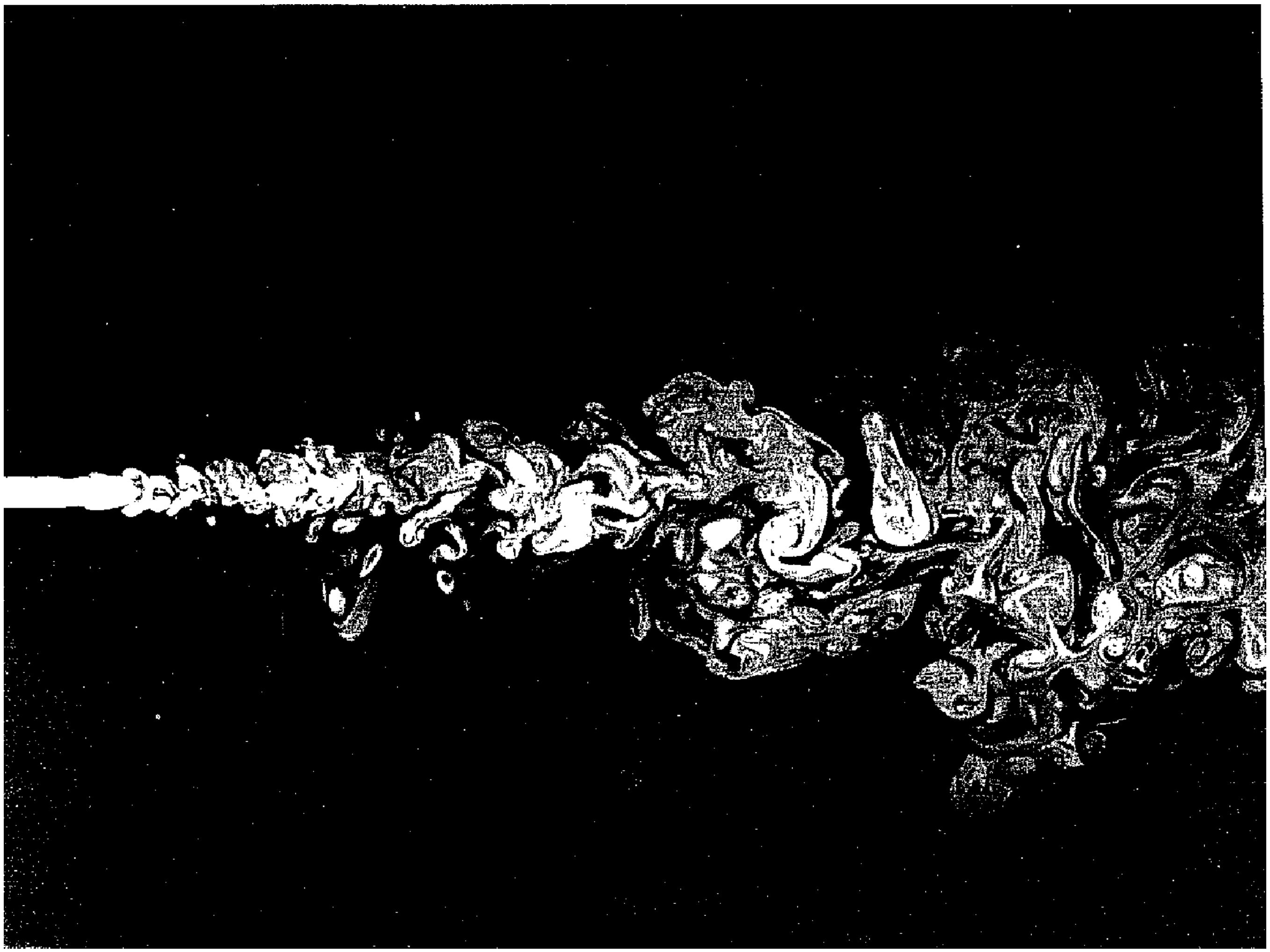
What is turbulence?

1. The state or quality of being turbulent; violent commotion, agitation or disturbance; disorderly character or conduct.

2. Of natural conditions: Stormy or tempestuous state or action.

3. Random fluctuations superimposed on mean velocity in flowing system.

A Turbulent Jet

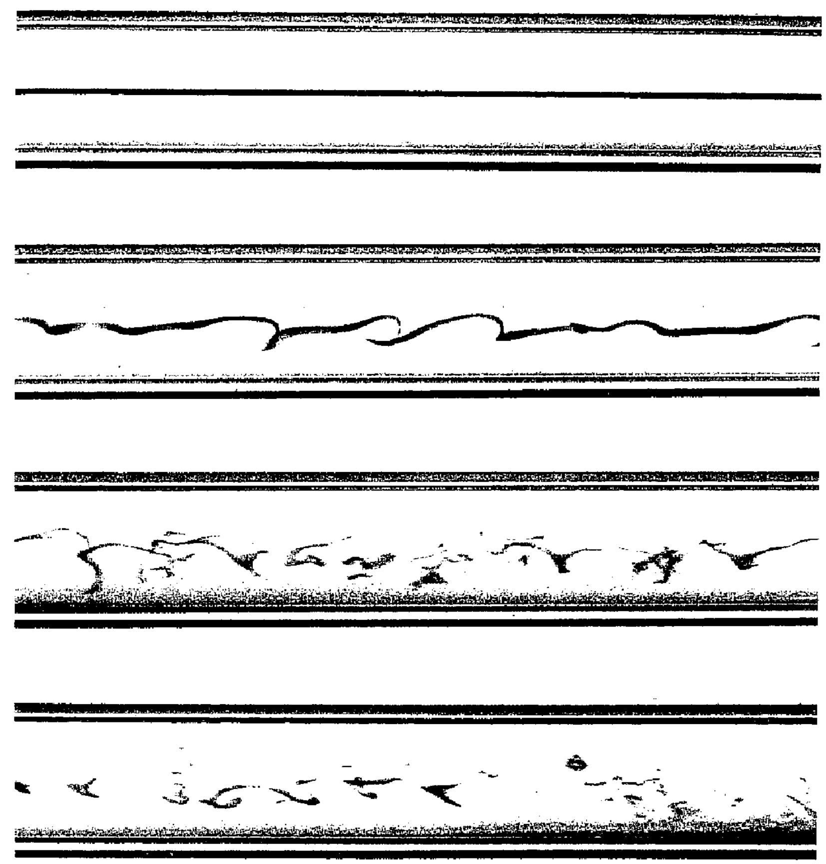


Example - Reynolds' Experiment

- Classic experiment performed in 1883.
- Set up co-axial horizontal pipes:
  - Colored water flows through central pipe.
  - Clear water through annulus.
- Gradually increase velocity of two streams and observe what happens.

Results

- Low velocity:
  - Central dyed stream flows parallel to pipe walls.
- Increasing velocity:
  - Central core starts to move radially.
  - Breaks-up.
- Higher velocity increases rate of core's dispersion.
- Increases rate of mixing.



Reynolds Number

- Ratio of inertial forces in flow to viscous stress resisting flow.

- Inertia:

$$I = \rho U^2$$

- Viscous stress:

$$\tau = \mu \frac{U}{D}$$

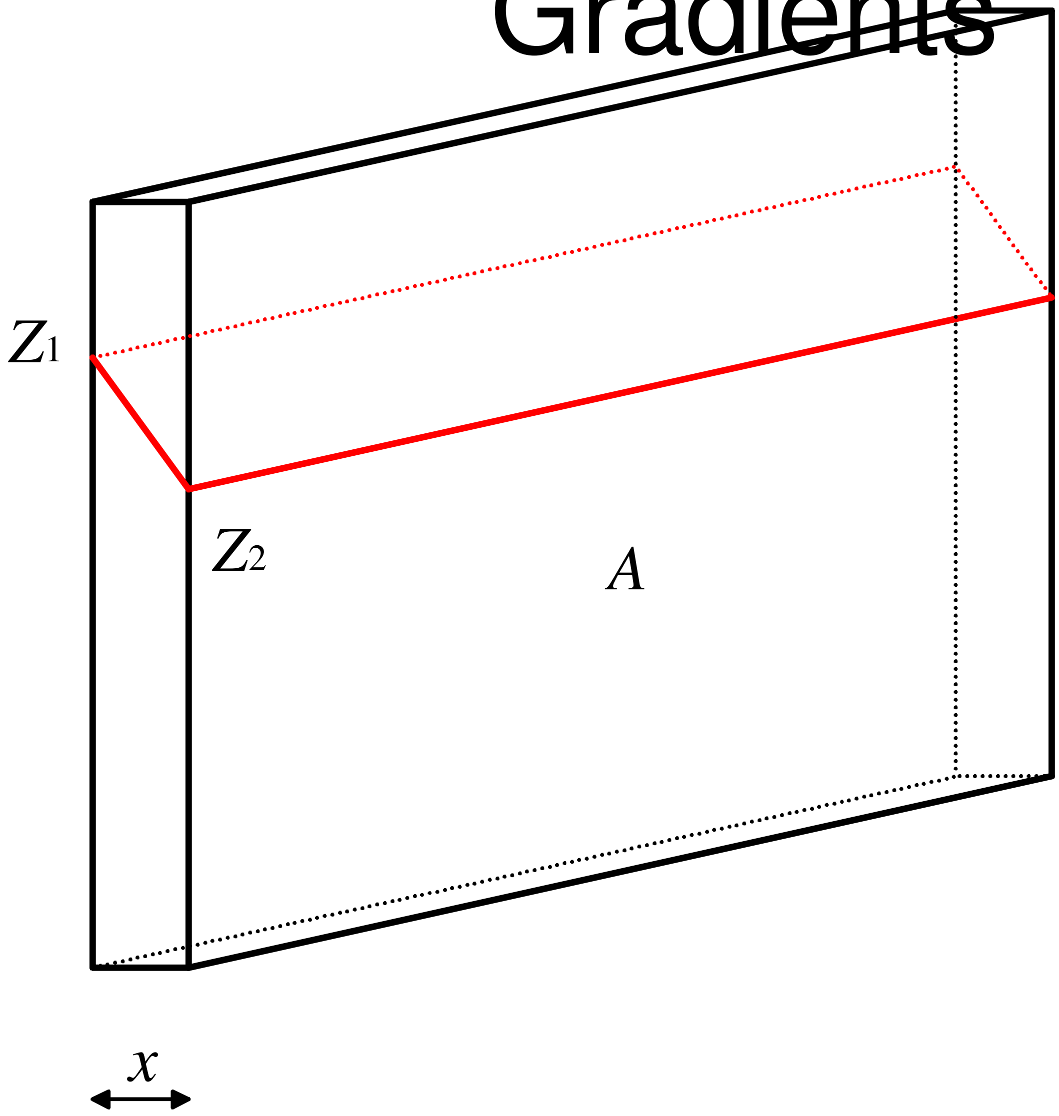
- Reynolds No:

$$Re = \frac{\rho U^2}{\mu \frac{U}{D}} = \frac{\rho U D}{\mu}$$

What is Happening?

- As velocity of streams increases, inertia dominates viscosity.
- Dyed central stream is mixing with outer clear stream.
- What is “driving force” that promotes mixing?
- A force is generated which transports the dye radially - perpendicular to the direction of flow.
- If no radial movement occurs, mixing can only happen by molecular diffusion. A slow process.
- Something else is diffusing. But what?

Gradients



$$\frac{Flux}{Area} = K\frac{Z_1 - Z_2}{x}$$

Transfer Processes

- Heat transfer:

$$\frac{Q/t}{A} = k\frac{(T_2 - T_1)}{x}$$

- Mass transfer:

$$\frac{M/t}{A} = D_{AB}\frac{(C_2 - C_1)}{x}$$

- Momentum transfer:

$$\frac{Mo/t}{A} = \mu\frac{(U_2 - U_1)}{x}$$

Momentum Transfer

- Force is rate of change of momentum per unit time.

$$F = \frac{Mo}{t}$$

- Driving force is velocity gradient:
  - Analogous to temperature or concentration gradient.

- Turbulent eddies carry momentum from regions of high to low velocity.

- As momentum is transferred, mass is transferred within the eddies.

$$j_A = \frac{1}{A}\frac{\mathrm{d}N_A}{\mathrm{d}t} = (D_{AB} + D_{EDDY})\frac{\mathrm{d}C_A}{\mathrm{d}x}$$

Eddy Diffusivity

- Eddy Diffusivity quantifies the rate at which momentum is transferred by turbulence.

- It is a property of the flow - not the fluid.

$$D_{EDDY} = u' l_E$$

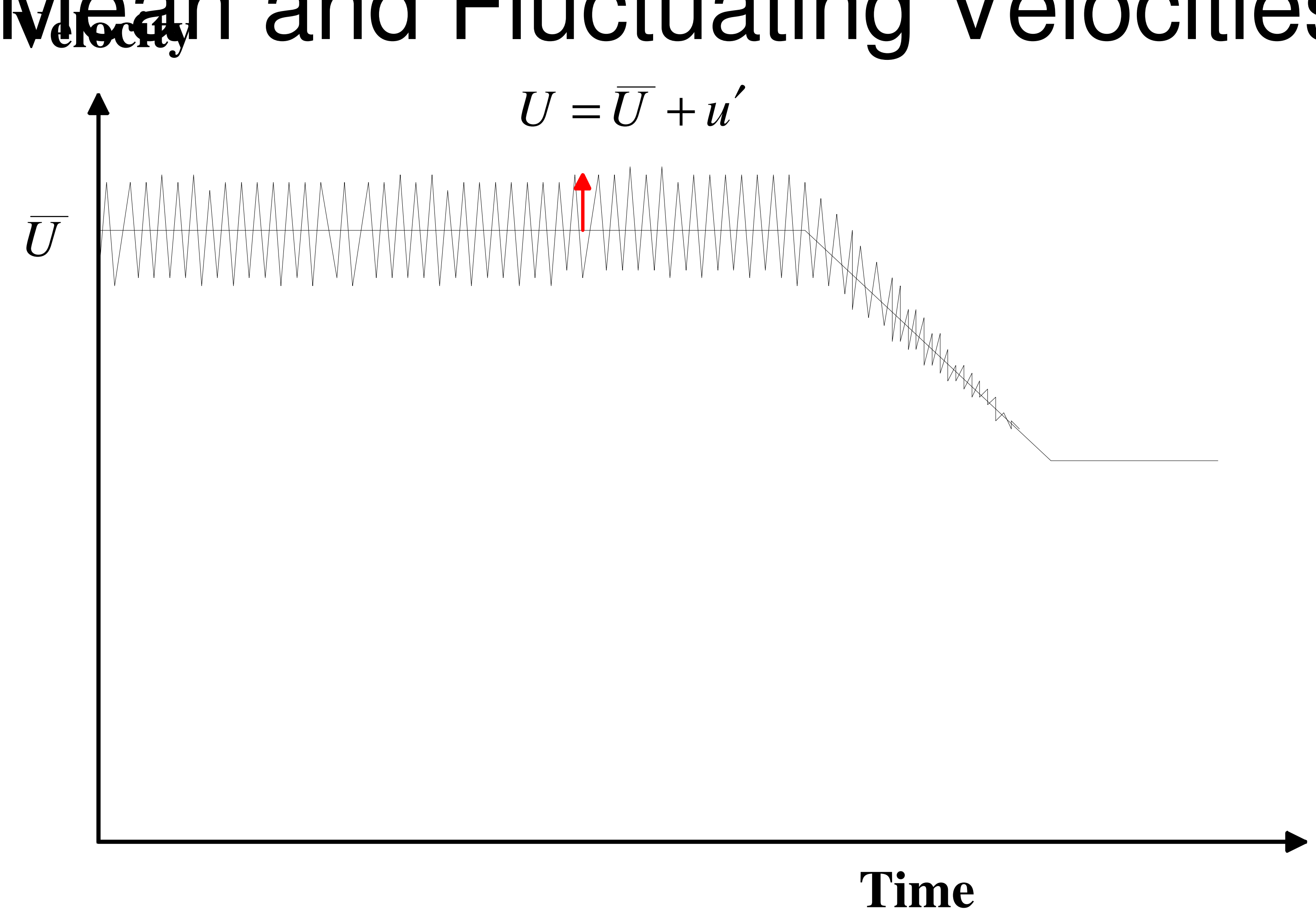
- What is *u′*?

- It is the fluctuating component of the fluid's velocity.

$$U = \overline{U} + u'$$

- In pipe flow, typically 5 % of mean velocity.

Mean and Fluctuating Velocities



Navier-Stokes Equation

- Laminar flow:
  - Four equations with four unknowns.
  - Can be solved.
- Turbulent flow:
  - Four equations with seven unknowns.
  - Cannot be solved directly.
- Need models to approximate turbulence quantities.
- Area of research and development.
- Computational Fluid Dynamics (CFD).

Example - Shear Stress

- Laminar flow:
  – Contribution due to mean velocities.

$$\tau_V = \mu \frac{\mathrm{d}U}{\mathrm{d}x}$$

- Turbulent flow:
  – Contribution due to fluctuating velocities.

$$\tau_T = \rho u'^2$$

- Total stress:

$$\tau = \tau_V + \tau_T = \mu \frac{\mathrm{d}U}{\mathrm{d}x} + \rho u'^2$$

- Need to know values of fluctuating velocity.
- Need to make approximation ………...

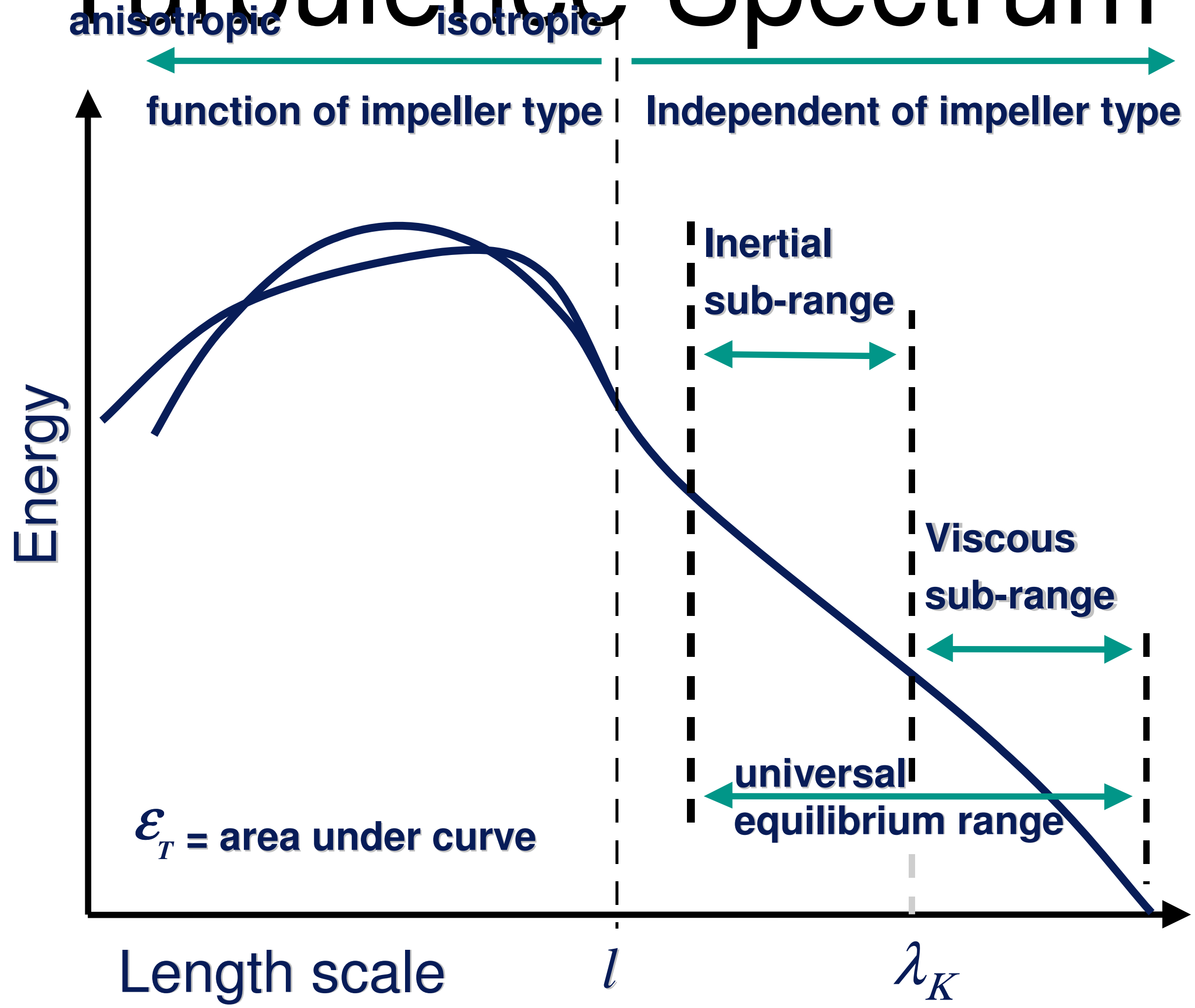
Example - Shear Stress

- One approach (one of many) ………...
- The concept of "eddy viscosity":

$$\tau = \tau_V + \tau_T = (\mu + \phi)\frac{\mathrm{d}U}{\mathrm{d}x}$$

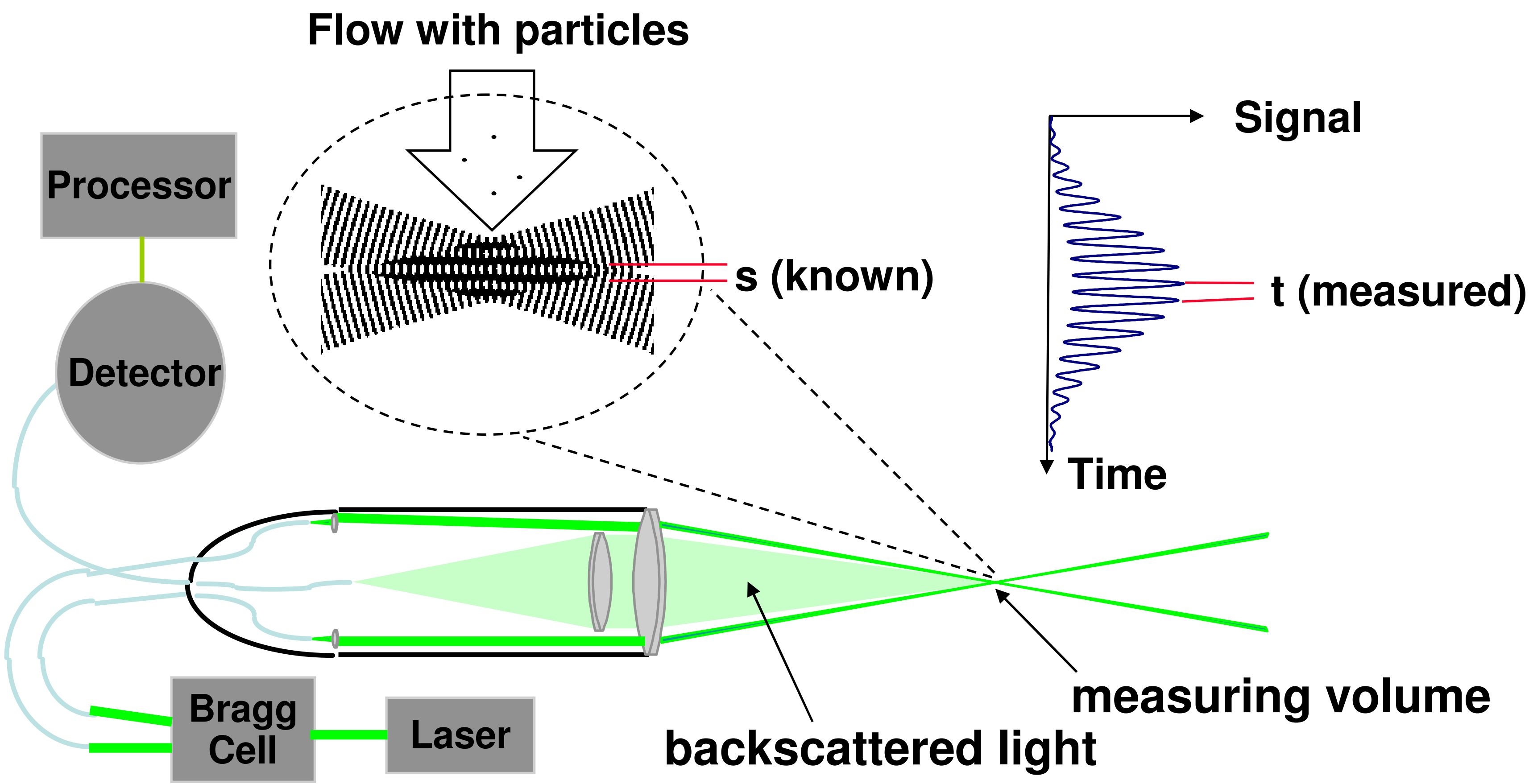
- Now write total stress in terms of mean velocity gradient.
- ϕ is a property of the flow - not the fluid.
- The turbulent stresses are several orders of magnitude higher than viscous stresses.

Turbulence Spectrum



Measurement of Spectrum - LDA

Velocity = distance/time



Eddy Length Scales

- Largest eddies are determined by size of equipment:
  - Blade diameter.
  - Blade width.
  - Vessel.
- Smallest eddies are at the Kolmogoroff Length Scale.
  - Size determined by fluid viscosity and local energy dissipation rate:

$$\lambda_K = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

$$Re_{EDDY} = \frac{u_K \lambda_K}{\nu} = 1$$

  - from dimensional analysis!
  - At Kolmogoroff Length Scale mixing occurs by diffusion between eddies.

Kolmogoroff Length Scale

$$Re_{EDDY} = \frac{u_K \lambda_K}{\nu} = 1$$

$$u_K \lambda_K = \nu$$

$$\varepsilon = \frac{u_K^3}{\lambda_K} \qquad \text{or:} \qquad u^3 = \varepsilon \lambda_K$$

$$\varepsilon \lambda_K^4 = \nu^3$$

$$\lambda_K = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4}$$

Energy Containing Eddies

- Most mixing processes take place at a scale between the large and Kolmogorof eddies.
- These are called the “energy containing eddies”:

$$u' \sim (\varepsilon l_E)^{1/3}$$

- ε is the local energy dissipation rate:
  - Energy / time mass $\rightarrow$ power input per unit mass.
- ε varies with position in an agitated vessel:
  - High near impeller - low near walls and liquid surface.
- Use mean or local depending on process.

Blending Miscible Liquids

- Expect blending rate to be proportional to eddy diffusivity?

$$\theta \sim \frac{T^2}{D_{EDDY}} \sim \frac{T^2}{u' l_E}$$

$$\theta \sim \frac{T^2}{\varepsilon^{1/3} l_E^{4/3}}$$

- Macro-scale process so, $l_E \sim D$:

$$\theta \sim \frac{T^2}{\varepsilon^{1/3} D^{4/3}} \sim \varepsilon^{-1/3} \left(\frac{T}{D} \right)^{4/3} T^{2/3}$$

- Supported by experimental results:
  - Implications for scale-up?
  - Different exponent on T / D ratio.

Drop or Bubble Formation

- Inertial forces due to turbulent fluctuations of flow are balanced by viscous forces and interfacial tension:

$$\rho_C (u')^2 \sim \mu_D \frac{u'}{d} + \frac{\sigma}{d}$$

- If dispersed phase viscosity is low:

$$(u')^2 \sim \frac{\sigma}{\rho_C d}$$

$$(\varepsilon l_E)^{2/3} \sim \frac{\sigma}{\rho_C d}$$

- Drops will be affected by eddies of the same size:
  - Convected by larger eddies.
  - Smaller eddies will have no effect.

Drop or Bubble Formation

- Substitute droplet size for eddy length scale:

$$(\varepsilon d)^{2/3} \sim \frac{\sigma}{\rho_C d}$$

$$d^{5/3} \sim \frac{\sigma}{\varepsilon^{2/3}\rho_C}$$

$$d \sim \varepsilon^{-2/5}\left(\frac{\sigma}{\rho_C}\right)^{3/5}$$

- This relationship has been found experimentally in stirred tanks, motionless mixers and high-speed dispersers:
  - Implications for scale-up?

Future Discussions

- Turbulence determines rates of many mixing processes.
- Experimental results and correlations show important factors in determining mixing rates (process results).
- We will always attempt to explain results from a fundamental physical basis:
  - Look for functionality.
  - Need to do experiments to find constants of proportionality.
- If such an explanation is possible, we have much higher degree of understanding and confidence:
  - Especially when looking at design and scale-up of equipment.

A NOTE OF PHYSICAL PROPERTIES

- Fluid and solids physical properties
- Density – liquids and gases – solids crystal or chemical density
- Viscosity – the resistance to deformation – to be discussed in detail
- Thermal – heat capacity and thermal conductivity
- Surface – surface and interfacial tensions and others

MIXING AND GEOMETRY

- Mixing equipment is characterized by complex geometry and many geometric variables
- Certainly compared to previously studied geometries
  - Pipes, blunt bodies etc.
- Fluid dynamics in complex geometries
- Correlations are often very geometric dependent

Impellers

- An agitator's impeller is a high flow - low head pump.

- Many of the rules that apply design of agitators are analogous to those used for pump design and pipe flow.

$$P = Q\Delta H$$

- Relationship between power, flow and head.

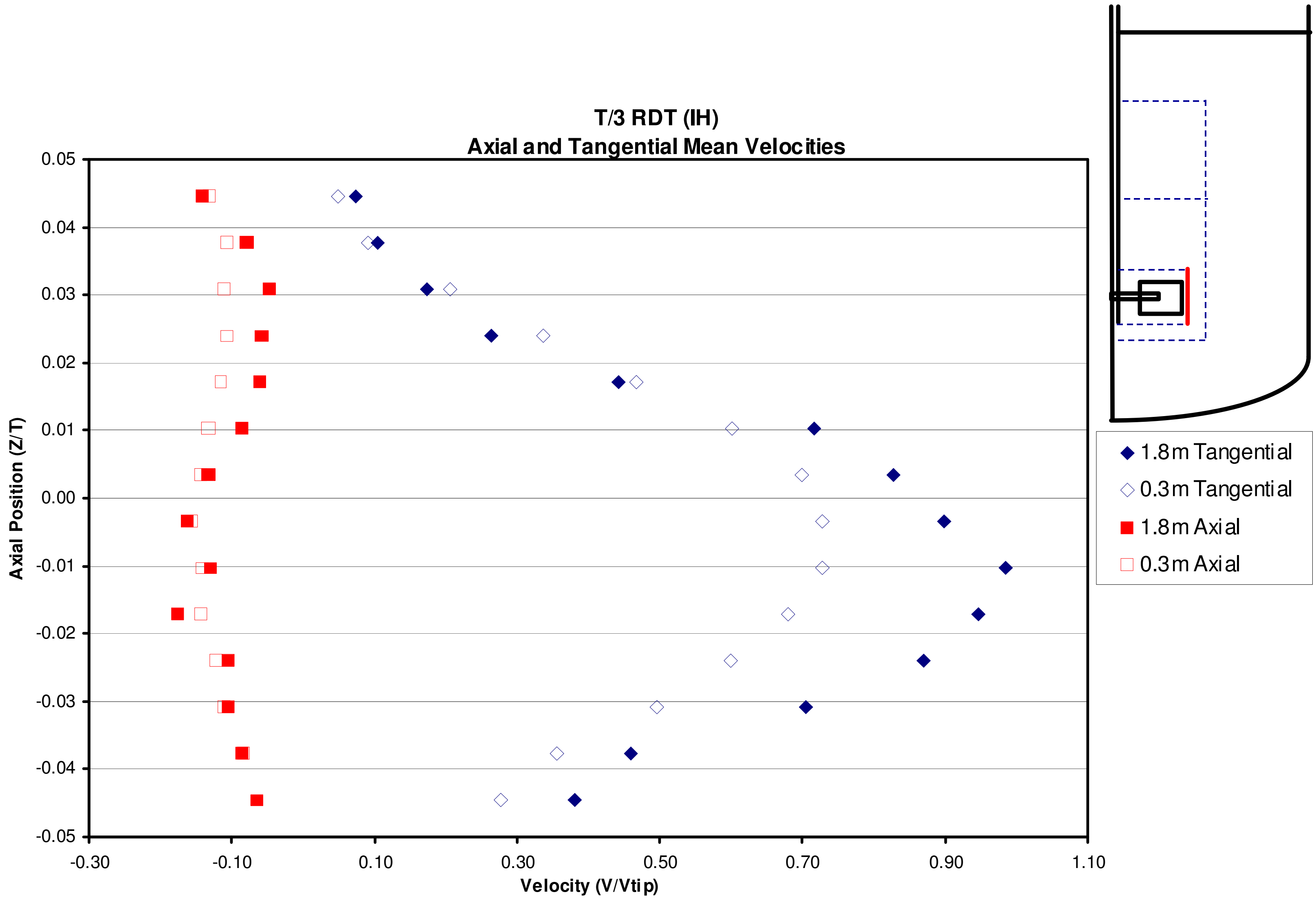
Flow

- How is flow measured?
- Laser-Doppler Anemometry.
- Define Flow number, *Fl*:

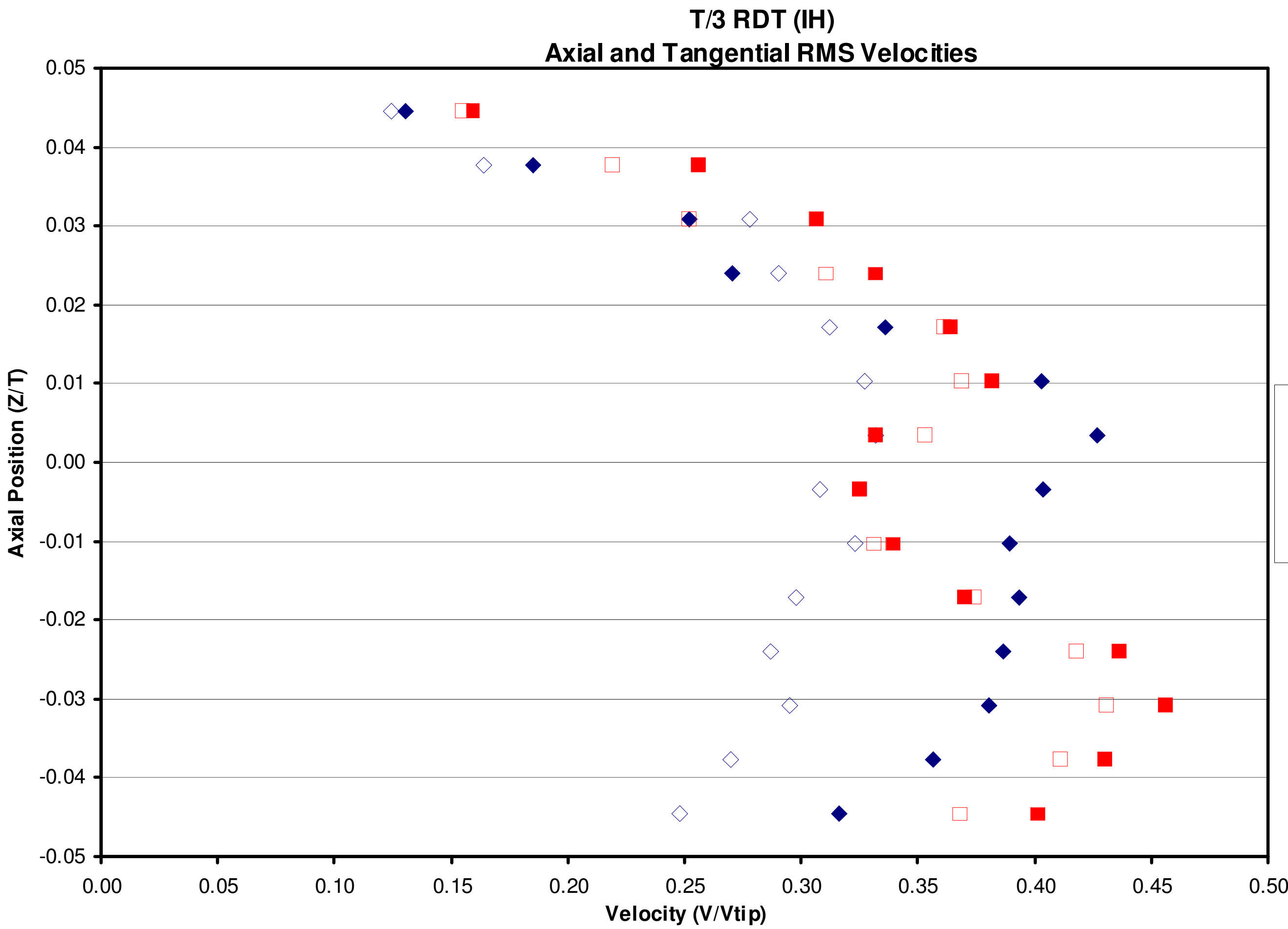
$$Fl = \frac{Q}{ND^3}$$

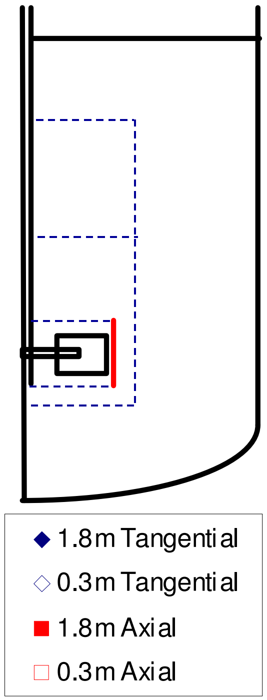
- *Q* is measured.
- *N* is known.
- *D* is known.

Rushton Turbine - Mean

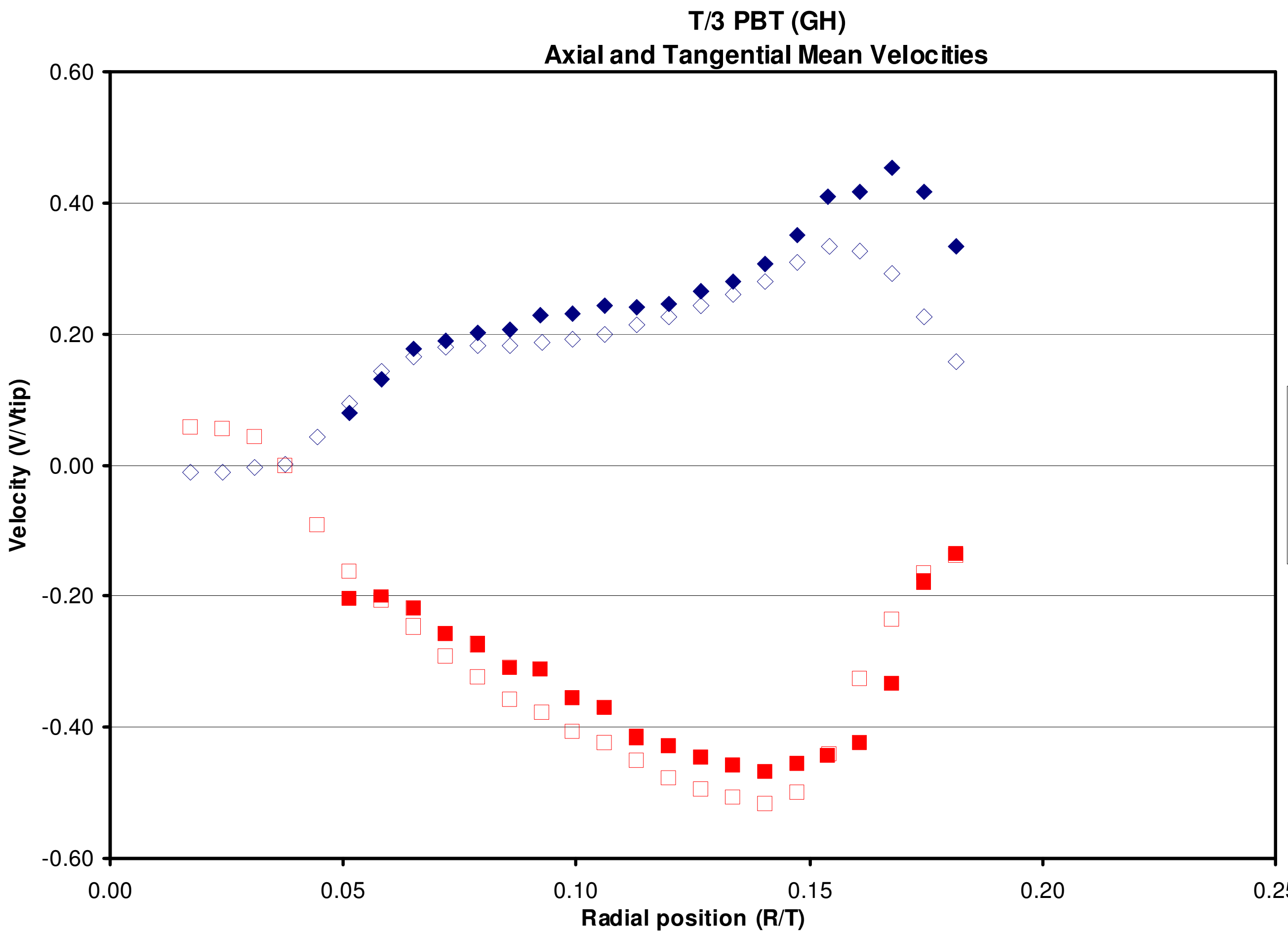


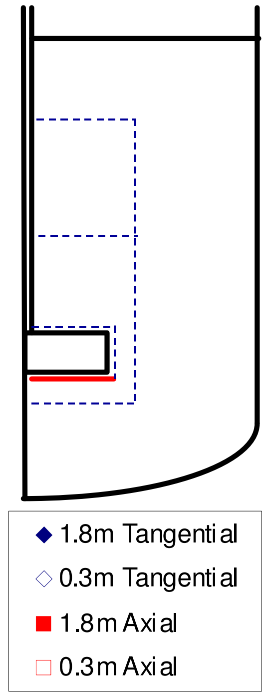
Rushton Turbine - Fluctuating



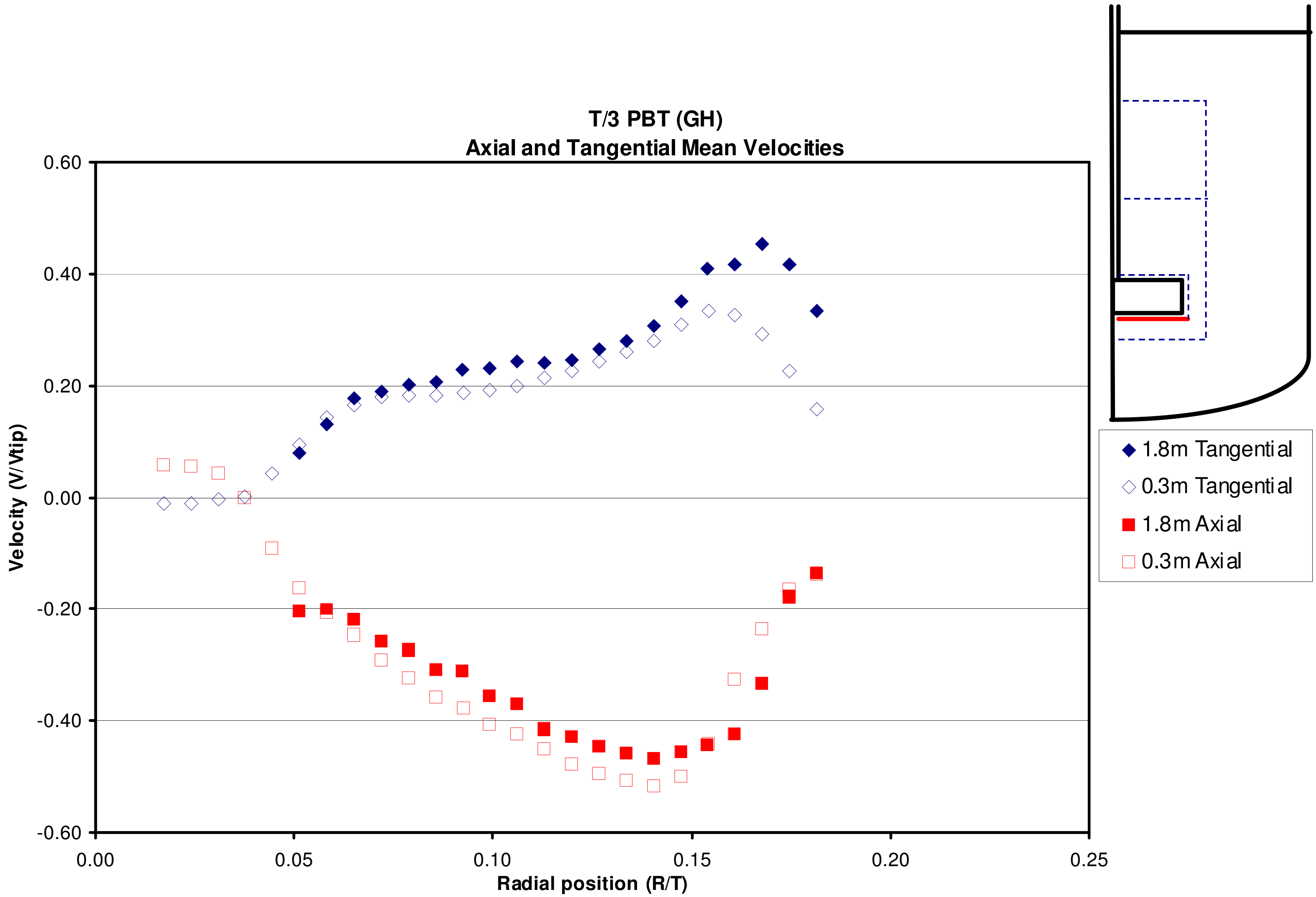


Pitched Blade Turbine - Mean





Pitched Blade Turbine -



Analysis

- Velocity measured at each position in discharge.
- Integrate velocities around discharge area.

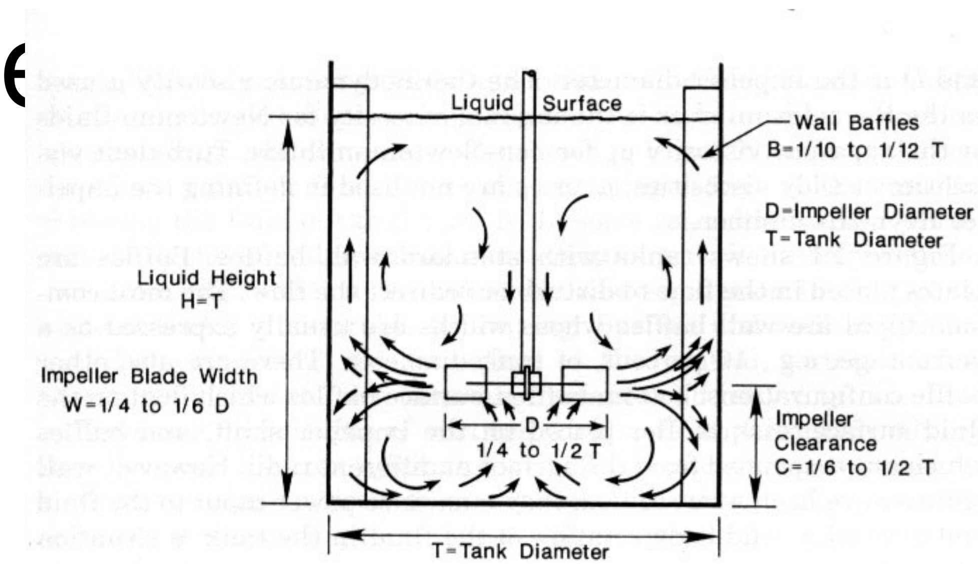
$$Q = \int U \mathrm{d}A$$

- What are limits of discharge area?
- Leads to problems when comparing results from different labs.
- Small differences.

Primary Flow

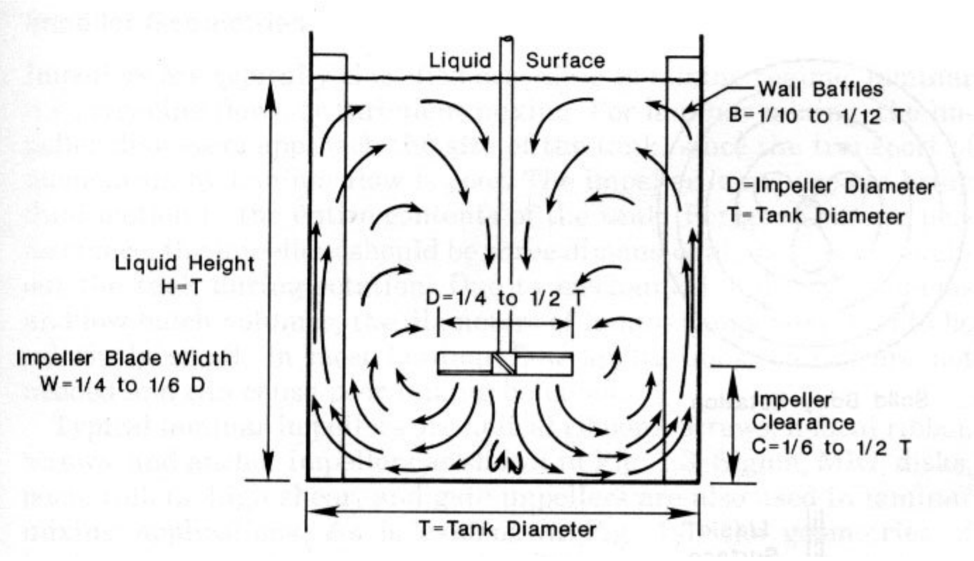
- Measure “primary” flow with LDA.
- This flow entrains surrounding fluid:
  - Secondary flow.
  - More on this when we talk about jet mixers.
- Entrained flow depends on primary flow and equipment geometry.

Discharge - Radial Flow Impe



- Discharge towards wall of tank.
- Draw fluid into impeller from above and below.
- Discharge area is vertical cylinder.
- Radial flow impellers:
  - Flat blade turbine.
  - Rushton turbine.
  - Smith turbine.
  - Bakker turbine.

Discharge - Axial Flow Impellers



- Discharge towards base of tank or liquid surface.
- Draw fluid into impeller from above or below.
- Discharge area is horizontal circle.
- Axial flow impellers:
  - Pitched blade turbine - blade angle 30 - 60 degrees, 45 most common
  - Hydrofoils.
  - Marine propellers.

Typical Flow Numbers

Impeller Type	Flow Number, *Fl*
Radial (4 blades)	0.6
Radial (6 blades)	0.7 – 0.85
Axial (4 blades)	0.8
Axial (6 blades)	0.9
Propeller	0.5
A310 Hydrofoil	0.56

Prediction of Flow Number

- Correlation of flow number as a function of power number.

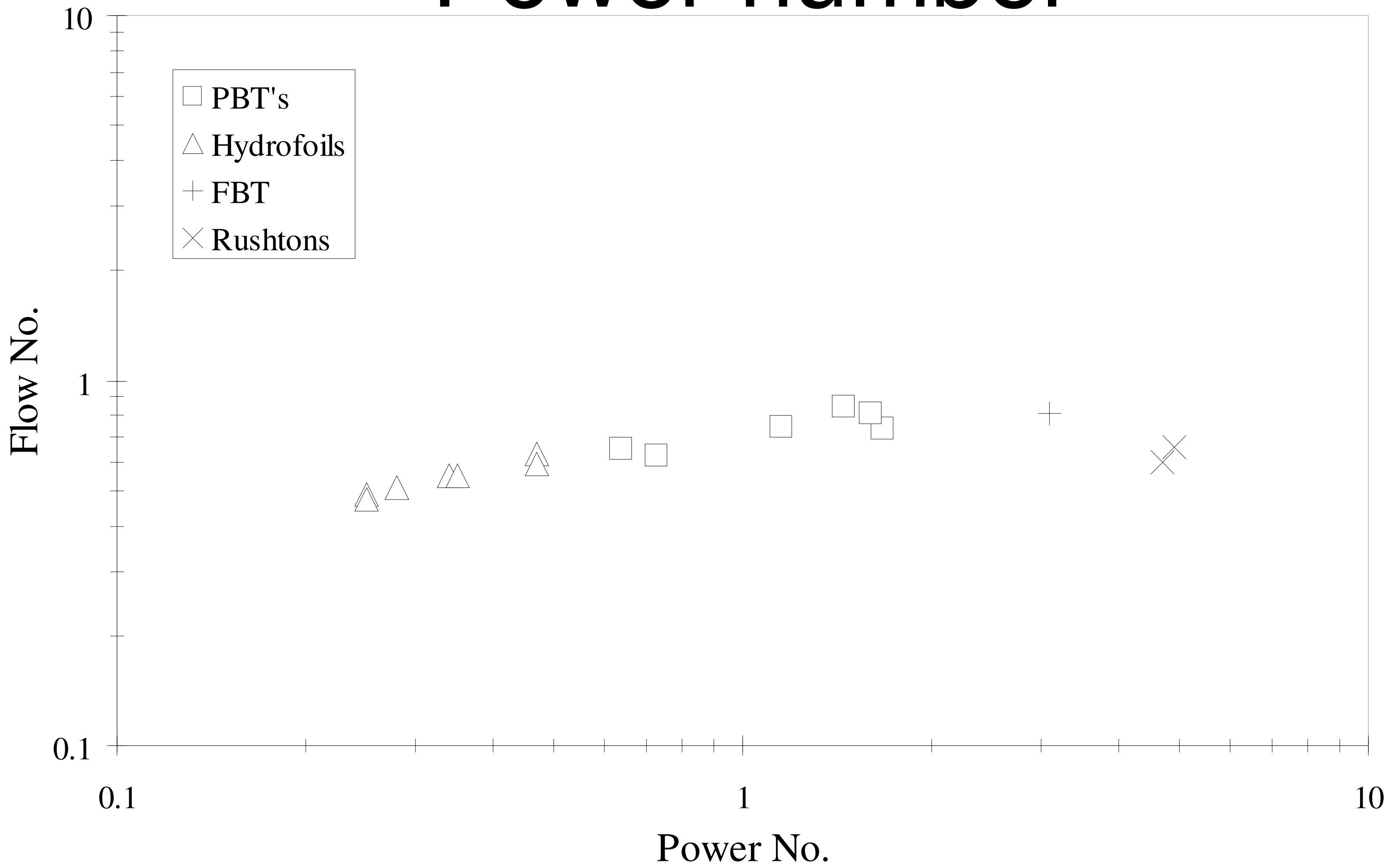
$$Fl = 0.77\,Po^{1/3}$$

- Works for axial flow impellers:
  - Hydrofoils.
  - Pitched blade turbines.

- Does not work for radial flow impellers.

- <u>NOTE:</u> Only holds for turbulent regime.

Plot of Flow number versus Power number



Power

- Need to calculate power because:
  - Important for process results.
  - Determines size of equipment.
  - Operating cost.
  - Mechanistic / Theory e.g: power input per unit mass.

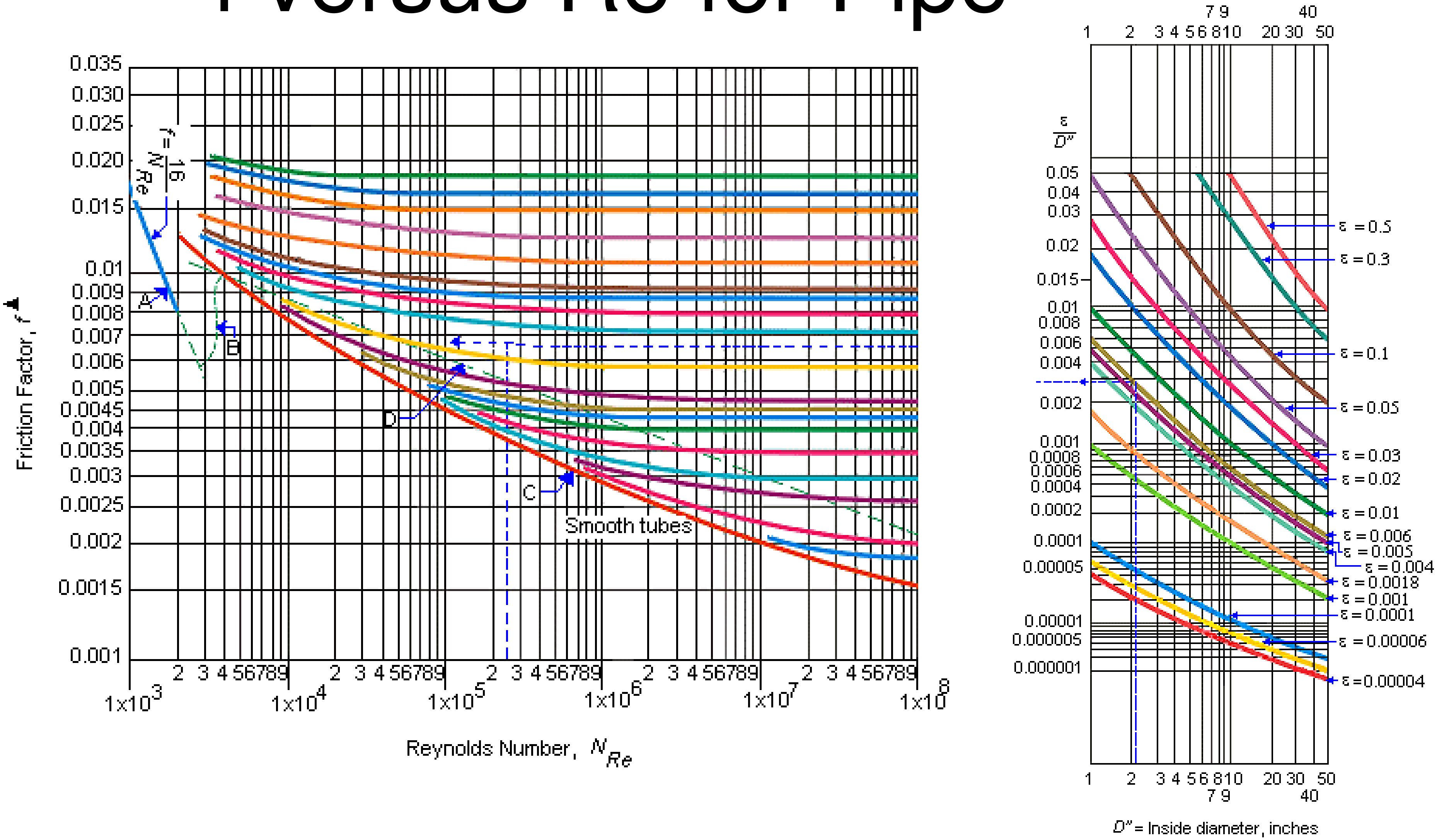
- Dimensionless group: Power number.

$$Po = \frac{P}{\rho N^3 D^5}$$

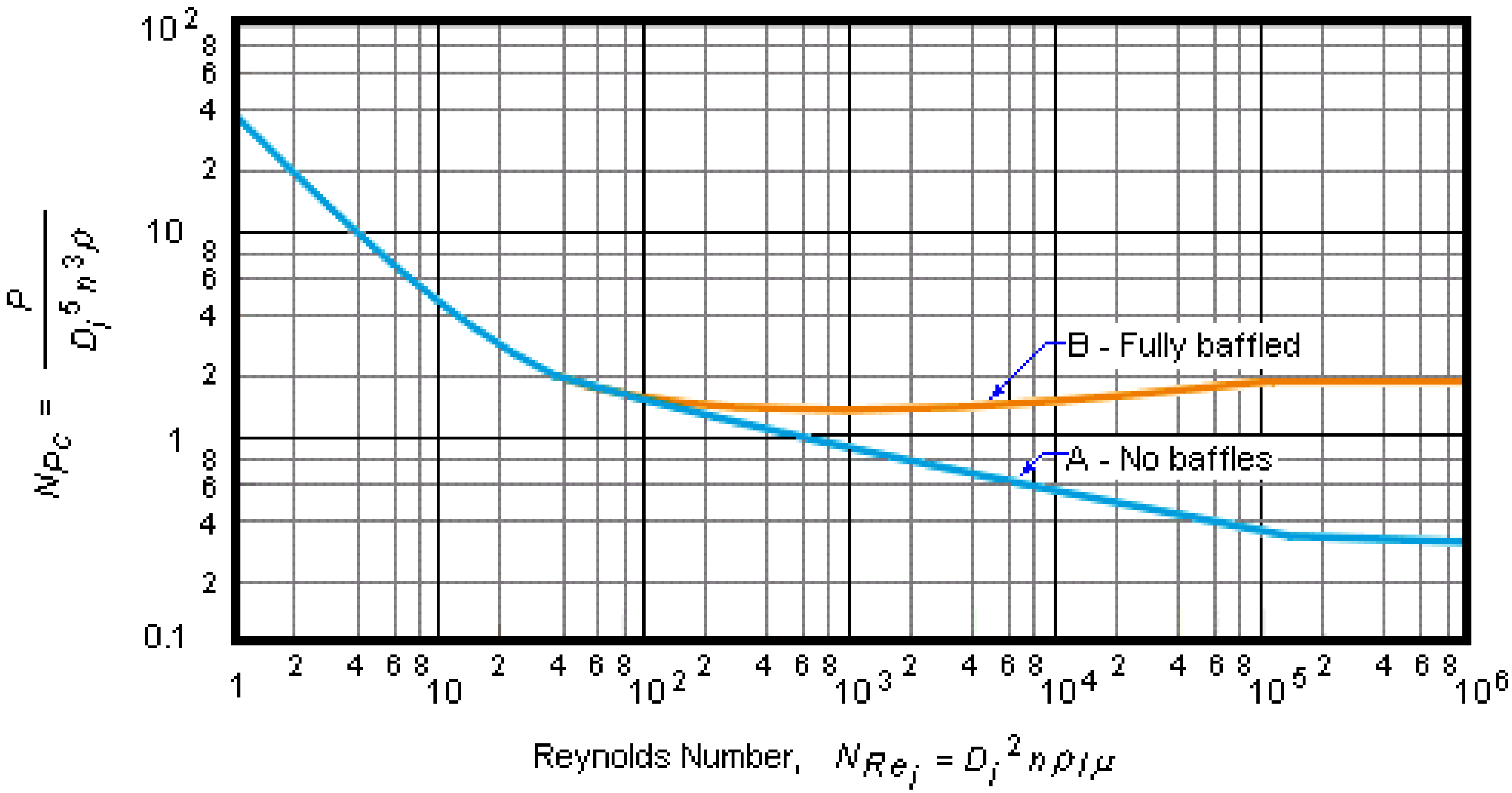
- Power number is a drag factor:
  - Analogous to friction factor in pipe flow.

- Power number is a function of impeller geometry.

f versus Re for Pipe Flow



Po versus Re for Standard Flat Paddles



Power Numbers under Turbulent Conditions
Shuie & Wong, Can. J. Chem. Engg., 62 (1984)

Impeller Type	Blade Angle	Number of Blades	D_w/D	P_o
FBT	90	6	0.2	5.0
CBT	90	6	0.269	4.0
CBT	90	4	0.154	4.6
PBT	45	4	0.231	1.74
PBT	45	2	0.231	1.2
Propeller	--	3	--	0.67
FBT	90	4	0.20	3.0
PBT	45	4	0.20	1.0

FBT-Flat Blade Turbine, CBT-Curved Blade Turbine, PBT-Pitched Blade Turbine

Power Numbers under Laminar & Turbulent Conditions
Prof. J.M. Smith, Univ. Surrey

$$Po = \frac{A}{Re} + B + \frac{C}{1000 + Re}$$

Impeller Type	Blade Angle	Number of Blades	A	B	C
FBT	90	6	67	3.2	1.8
CBT	90	6	67	2.6	2.2
PBT	45	4	49	1.5	0.3
PBT	60	4	50	4.0	1.0
Propeller	--	3	47	0.9	0.3
FBT	90	4	50	4.0	1.0

FBT-Flat Blade Turbine, CBT-Curved Blade Turbine, PBT-Pitched Blade Turbine

Turbulent and Laminar Relationships

- Turbulent regime:

$$P = Po\rho N^3 D^5$$

- Power number is constant (in a baffled vessel).
  - Value is dependent on impeller geometry.

- Laminar regime: $$Po = \frac{K_P}{Re}$$

$$P = \frac{K_P}{Re}\rho N^3 D^5 = K_P \mu N^2 D^3$$

- Power is inversely proportional to *Re*.
  - Value of K_P is dependent on impeller geometry.

Torque

- Forces:
  - Impeller exerts forces on fluid.
  - Fluid exerts equal and opposite force on impeller blades.

- Torque is the “twist” force acting on the agitator shaft.

$$Tq = \frac{P}{2\pi N} = \frac{Po\rho N^3 D^5}{2\pi N}$$

$$Tq = \frac{Po\rho N^2 D^5}{2\pi}$$

- Measure of the size of equipment:
  - Shaft diameter.
  - Blade thickness.
  - Gear box size.

Mixing Tank Equipment

- Tanks/Vessels
- Right Cylinder most common
  - Height-to-diameter ratio - 0.8 to 1.5
  - Dished bottom and flat bottom
  - Taller vessels are used in some applications.
- Top Entering Shafts
  - Rotational, vertical
- See http://www.mixing.net/ for links to Mixing Equipment Vendors

Mixing Tank Baffles

- Mixing Tank without baffles
  - Predominantly rotational flow (solid-body rotation)
  - No interchange between top and bottom
- Vertical Baffles
  - Turn rotational component into vertical component
  - Increase top to bottom flow
  - Always specify baffles for turbulent flow
- Alternatives to Baffles (for small vessels)
  - Angle mount shaft
  - Off-center vertical mount shaft
  - Side-entering shaft

Standard Baffle Configuration

- Full Baffling
  - 4 Vertical Baffles at full length of straight side of tank
  - Baffle Width, $B_w = T / 12$
  - Offset from Wall = $T / 72$ (or $B_w / 6$)

- Partial Baffling Alternatives
  - 1/2 Height, 1/2 Width, 2 Baffles
  - Results in some surface vortex

- *Po* (Baffled) is greater than *Po* (Unbaffled) by 20-50%

MULTIPLE IMPELLERS AND SHAFTS

- About 80% of all agitators have more than one impeller
  - Uniformity of process result over whole tank
  - All impellers same speed
  - Tall tanks
- Assume additive
  - Calculate individual powers
  - Good for power when impellers are about one impeller diameter apart
  - Other wise some what less
- Mix time - assume reciprocals mix times are additive
  - Take away height correction

- Multiple shafts – nature of flow changes with time
  - Batch
  - Different speeds – anchor can act as baffle
  - Only recently studied – pretty independent

Power, Flow and Head

- Impeller generates flow and head.

- Tip Speed = πND
  - 2 - 6 m / s
  - Defines maximum velocity.

$$P = Q\Delta H$$

$$\Delta H = \frac{P}{Q} = \frac{Po\rho N^3 D^5}{Fl N D^3}$$

$$\Delta H = \frac{Po}{Fl}\rho N^2 D^2$$

- For axial flow impellers:

$$\Delta H = 1.30\rho(Po^{1/3} ND)^2$$

Example Calculations

- Pitched blade turbine:
  - Diameter: 1 m
  - Operating speed: 84 RPM
  - Power number: 1.74
  - Fluid: Water

$$P = Po\rho N^3 D^5$$

- Power:

$$P = 1.74 \times 1000 \times (84/60)^3 \times 1.0^5$$

$$\boldsymbol{P = 4775 \text{ W} \text{ (or 6.40 HP)}}$$

- Flow:

$$Q = FlND^3 = 0.77 Po^{1/3} ND^3$$

$$Q = 0.77 \times 1.74 \times (84/60) \times 1.0^3$$

$$\boldsymbol{Q = 1.297 \text{ m}^3/\text{s} \text{ (or 20553 GPM)}}$$

Example Calculations

- Torque:

$$Tq = \frac{Po\rho N^2 D^5}{2\pi}$$

$$Tq = \frac{1.74 \times 1000 \times (84/60)^2 \times 1.0^5}{2\pi}$$

$$\boldsymbol{Tq = 542.8 \text{ Nm}}$$

- Head:

$$\Delta H = 1.30\rho(Po^{1/3} ND)^2$$

$$\Delta H = 1.30 \times 1000 \times (1.74^{1/3} \times (84/60) \times 1.0)^2$$

$$\boldsymbol{\Delta H = 3686 \text{ Pa (or } 0.376 \text{ m)}}$$

Characteristic Velocities

- Tip Speed = πND
- Thrust Velocity: Flow / Pumping Area:
- Axial Impeller:

$$U_{Th} = \frac{Q}{A_I} = \frac{FlND^3}{(\pi/4)D^2}$$

- Radial Impeller:

$$U_{Th} = \frac{Q}{A_I} = \frac{FlND^3}{\pi Dw}$$

M5
MIXING CONCEPTS II

Blending Liquids

BLENDING LIQUIDS

- Low viscosity – water like
- In turbulent flow
- Usually not controlling
- Most important when fast chemical reactions are involved
  - Will not be discussed

ChemScale Method

- Need method to rate motion in tanks.
- Bulk Fluid Velocity: Flow / Vessel Area.
- Use Bulk Fluid Velocity as criterion for describing motion:
  - Combines Tank Size and Impeller Effect.
- Little turbulence is required with homogeneous liquids:
  - Bulk Flow or Pumping is preferred.
- Standardize:
  - 45° Axial-4 Impeller (45° Pitched Blade Turbine).
  - Off-bottom Clearance, *C*.

ChemScale Method

- Rate Bulk Velocity on 1-10 Scale
  - Low: ChSc = 1: 6 ft / min
  - Medium: ChSc = 5: 30 ft / min
  - High: ChSc =10: 60 ft / min

- Correct for *Re* effect:
  - Increase viscosity reduces pumping ability of impeller.
  - Crude method but often good enough.

$$BFV = \frac{Q}{A_T} = \frac{FlND^3}{(\pi/4)T^2}$$

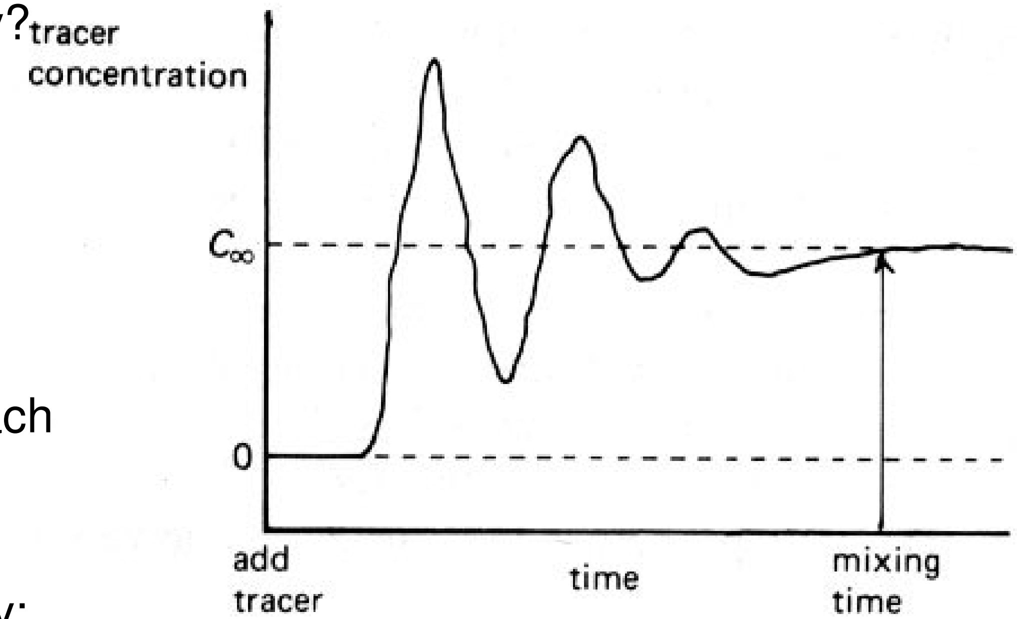
$$BFV \propto FlND\left(\frac{D}{T}\right)^2$$

BLEND TIME

- How long does it take to become uniform after a change?
- Sampling
- Batch blending
- Etc.

Blend Time

- How fast to get to Homogeneity?
- Measurements - Batch Stirred Tank:
  - Color Change - somewhat arbitrary
  - Conductivity or pH - approach to steady state
- Approach to Average Uniformity:
  - 95% approach (or 5 % of steady state).
  - Extrapolation along exponential decay curve.



$$\Delta c' = \exp(-k\theta)$$

Blending Mechanism

- Concentration fluctuations decay exponentially.
- 95% homogeneity when $\Delta c' = 0.05$:

$$\theta_{95} = -\frac{\ln(\Delta c')}{k}$$

$$\Delta c' = 0.05$$

$$\theta_{95} = -\frac{\ln(0.05)}{k} = \frac{3}{k}$$

- If time to certain degree of homogeneity is known, time to different degree can be calculated:
  - *k* can be calculated.
  - Used to calculate blend time to different degree of homogeneity.

Blend Time in Turbulent Regime

- Correlation for estimation of blend time in agitated vessels:
  - $0.33 < D / T < 0.50$.
  - $C / T = 0.33$.
  - $0.50 < H / T \leq 1.00$.

$$\theta_{95} = \frac{5.40}{Po^{1/3} N} \left(\frac{T}{D} \right)^{1.5} \left(\frac{H}{D} \right)^{0.5}$$

- In turbulent regime (in baffled vessel), *Po* is constant.

- For a given impeller / vessel geometry:

$$N\theta_{95} = C$$

Impeller Efficiency

- Power:

$$\theta_{95} = \frac{5.40}{Po^{1/3}N}\left(\frac{T}{D}\right)^{2}$$

$$\theta_{95} \propto \bar{\varepsilon}^{-1/3}\left(\frac{T}{D}\right)^{1/3} T^{2/3}$$

- Conclusions (at the same power input per unit mass):
  - Different impellers with same *D* / *T* will give same blend time.
  - Scaling-up increases blend time by scale factor raised to 2/3 power.
  - Compare with theoretical turbulence model.

- Torque:
  - Impeller with low power number must run at higher speed.
  - Higher speed $\rightarrow$ lower torque.
  - Hydrofoil impellers need same power but lower torque to achieve blend time.

FOURIER NUMBER

- A relation between mix time and physical properties

- Moderate use

- $Fo = \mu * \theta / \rho / T^2$

OTHER EFFECTS

- Physical property differences between what is added and bulk
- Density effects
  - Not significant
- Viscosity effects
  - Can be significant if add at quite region
  - Can increase time – acts like dissolving

Transitional Regime - Experimental

- Dimensionless Blend Time:
  - Constant of proportionality dependent on *Po*, *D* / *T*.

$$N\theta \propto Re^{-1}$$

- Power Number:

$$Po = K$$

- Experiments show three dimensionless groups in transitional regime:

$$Po^{1/3} Re = \frac{186}{\sqrt{Fo}}$$

$$N\theta_{95} = \frac{186^2}{Po^{2/3} Re} \left(\frac{T}{D} \right)^2$$

$$N\theta_{95} \propto Re^{-1}$$

Expand Dimensionless Groups

$$\theta_{95} = \frac{186^2 \mu}{Po^{2/3} \rho N^2 D^2} \left(\frac{T}{D} \right)^2$$

- Blend time is proportional to fluid viscosity.
- Re-arrange to express in terms of power input, etc.

$$\theta \propto \left(\frac{1}{\varepsilon} \right)^{2/3} \left(\frac{T}{D} \right)^{2/3} \frac{\mu}{\rho} T^{-2/3}$$

- Blend time reduces on scale-up?
- Implications for researchers working in lab?

Boundary between Regimes

- Solve two correlations:

$$Po^{1/3}Re = \frac{5.40}{Fo} \qquad\qquad Po^{1/3}Re = \frac{186}{\sqrt{Fo}}$$

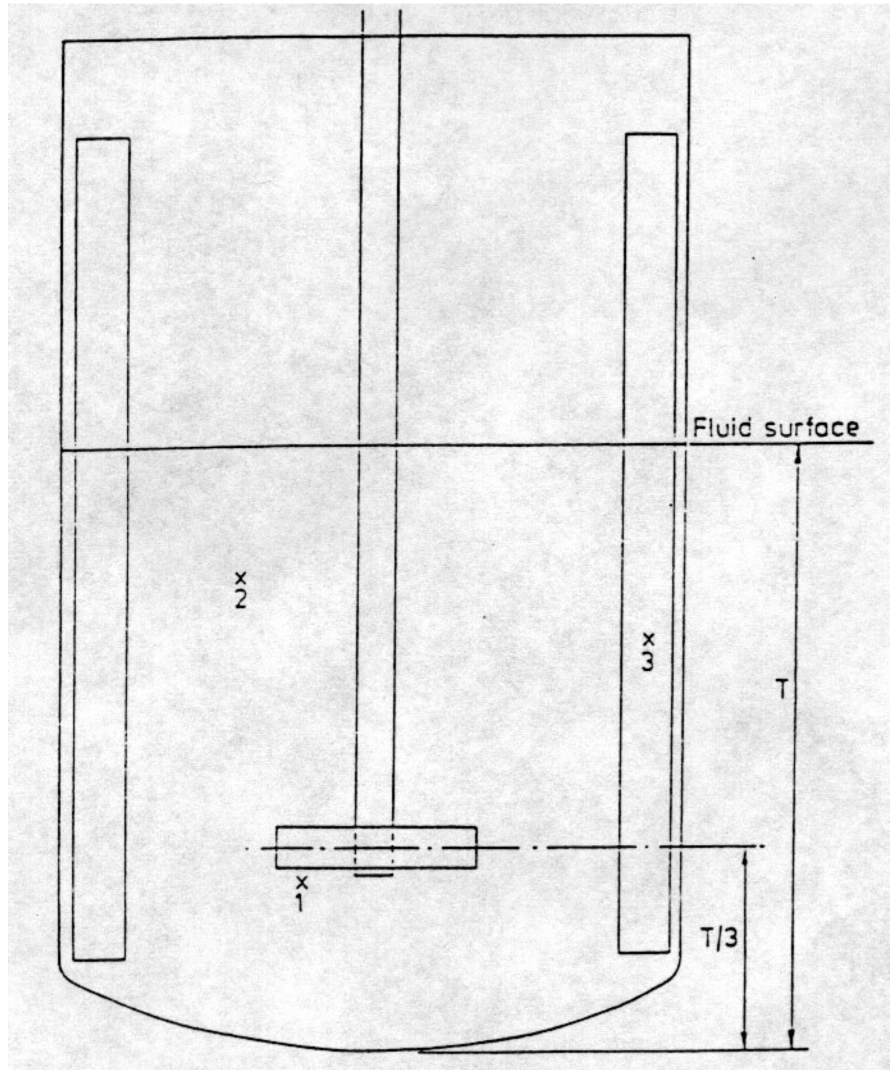
- At boundary of two regimes:

$$\frac{1}{Fo} = 1186 \qquad\qquad Po^{1/3}Re = 6404$$

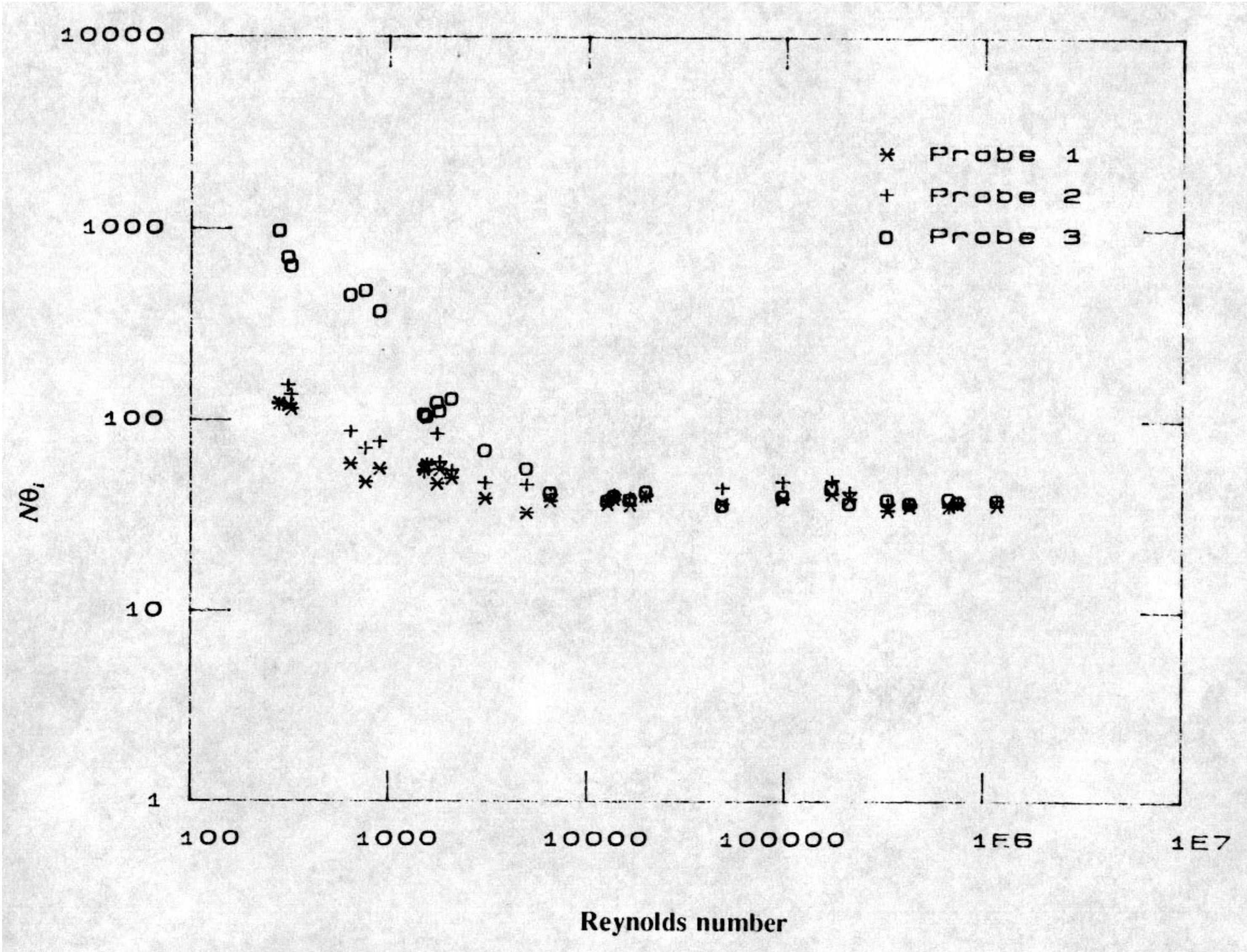
- Values are independent of impeller type.

Blend Time versus Position

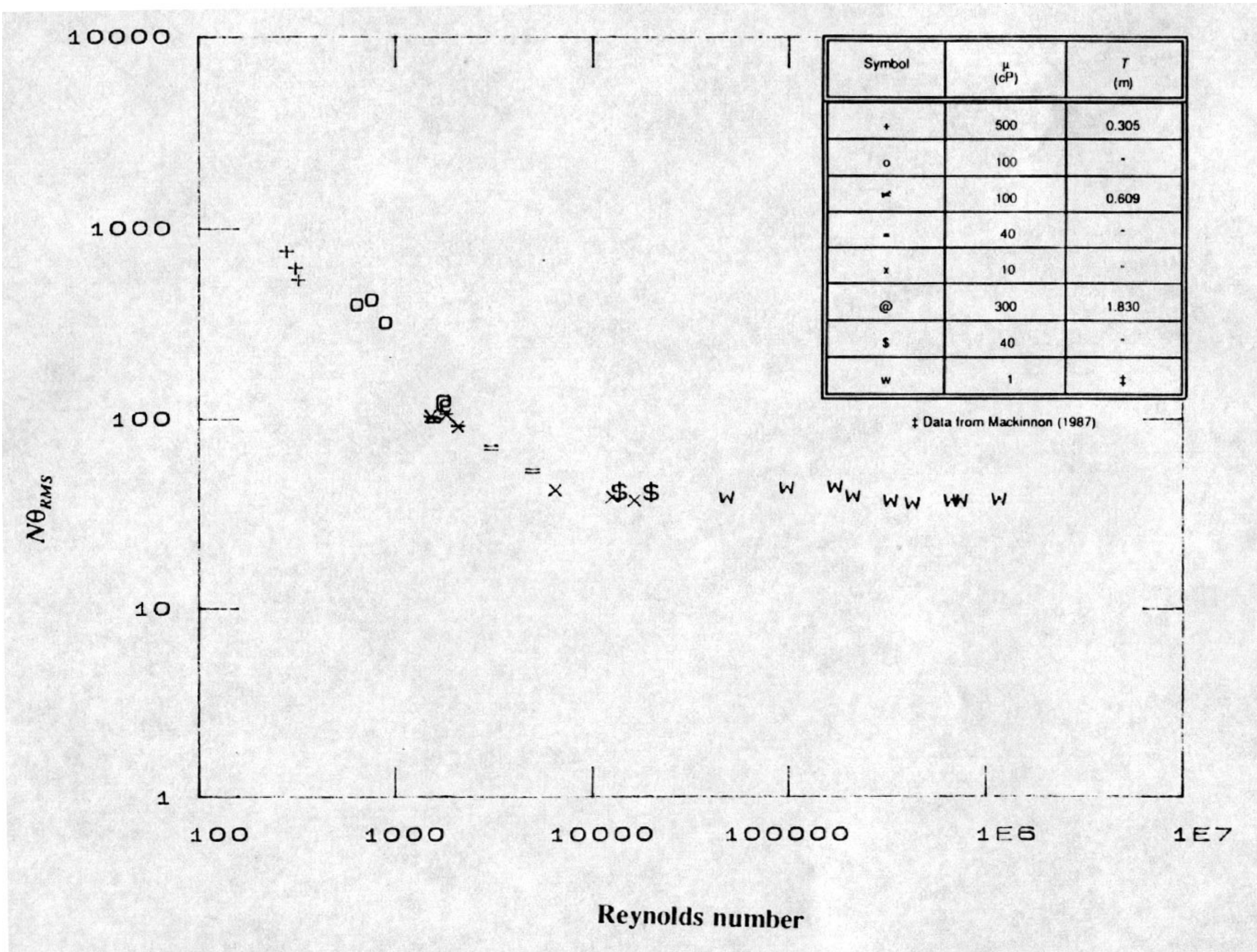
- Experimental set-up:
- Three probes in regions of different mixing intensity:
  - 1 - Under Impeller
  - 2 - Between Shaft and Wall
  - 3 - Behind Baffle



Results for Pitched Blade



Results for Pitched Blade



Conclusions

- In Turbulent Regime:

$$N\theta_1 = N\theta_2 = N\theta_3$$

- In Transitional Regime:

$$N\theta_1 < N\theta_2 < N\theta_3$$

  - Degree of deviation increases as Reynolds number decreases.
  - Blend Time for whole vessel is weighted by longest individual time.

- Impeller region is turbulent (Blend time and Power No.).

- Viscosity damps intensity of turbulence away from impeller.

Which Regime?

- Need to know if impeller operates in turbulent or transitional regime:
  - Which correlation to use for blend time?

- Designing new vessel and agitator.

- Rating existing vessel and agitator for new duty.

- How far can one go with turbine impellers?

Laminar Regime

- Boundary between transitional and laminar regimes:

$$Re < 200: \qquad N\theta \propto Re^{-10}$$

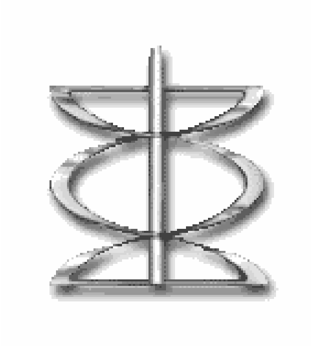
$$Re < 50: \qquad Po \propto Re^{-1}$$

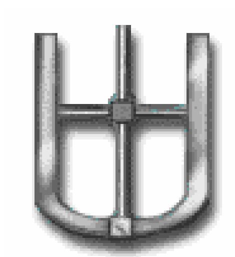
- Blending performance becomes laminar before Power No. starts to rise.
  - Blend time for vessel governed by slowest mixing region.
  - Slow near wall, behind baffles, at surface.
  - Turbulence still being generated near impeller.
- May be possible to use turbine at lower Reynolds numbers:
  - Depends on process requirements (e.g. cycle time).

Impeller Selection

$D / T \approx 0.95$

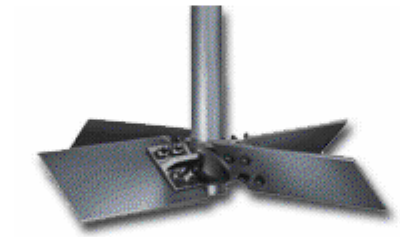
$0.3 < D / T < 0.5$

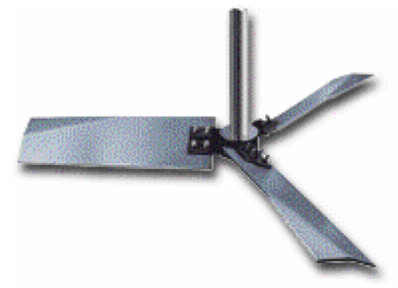


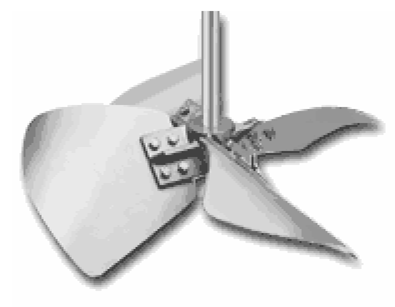


Increasing μ

Increasing *Re*







Impeller Selection for Laminar Blending

- Blending vessel contents relies on convection of fluid from impeller zone to wall and back again.
- As viscosity rises, pumping capability of turbines reduces.
- Need “positive-displacement” impeller.
- Close-clearance - $0.90 < D / T < 0.98$.
- Anchors and Helical Ribbons.
- Use Helical Ribbons.

Helical Ribbon Power Consumption

- Equation for predicting power consumption:

$$P = Po\rho N^3 D^5$$

- In the laminar regime:

$$Po = \frac{K_P}{Re} = \frac{K_P \mu}{\rho N D^2}$$

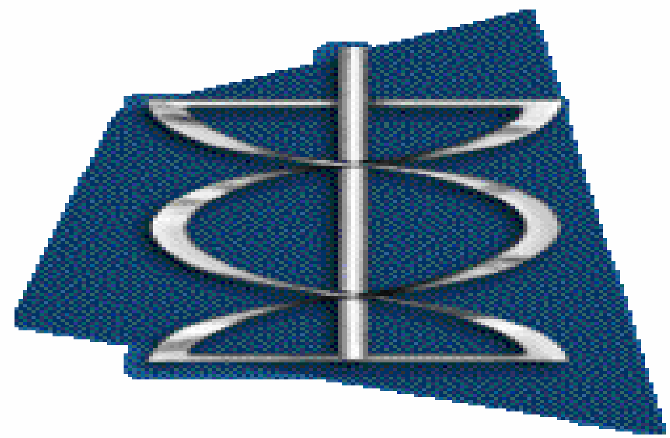
- Combining:

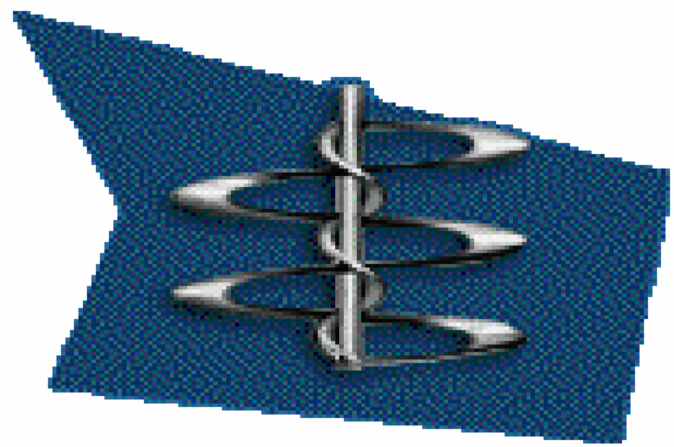
$$P = K_P \mu N^2 D^3$$

- For turbine impellers:50 < K_P < 70.
- For Anchors: $K_P = 225$.
- For Helical Ribbons: $K_P = 350$.

Helical Ribbons

- Single or Dual Flight.
- May have Central Auger.
- Ribbon width - 8 - 10 % of diameter.
- Pitch = Height of one turn.
- Clearance = Gap between impeller and vessel wall.





Anchors versus Ribbons

- Helical Ribbon:
  - Produce 3-D flow pattern.
  - Good mixing.
  - Higher power.

- Anchors:
  - Produce strong tangential flow.
  - Little axial flow.
  - Poor overall mixing.

Blend Time

- For Rieger's eight helical ribbons:

$$N\theta = 896 \times 10^3 K_P^{-1.69}$$

- No fundamental physical basis.

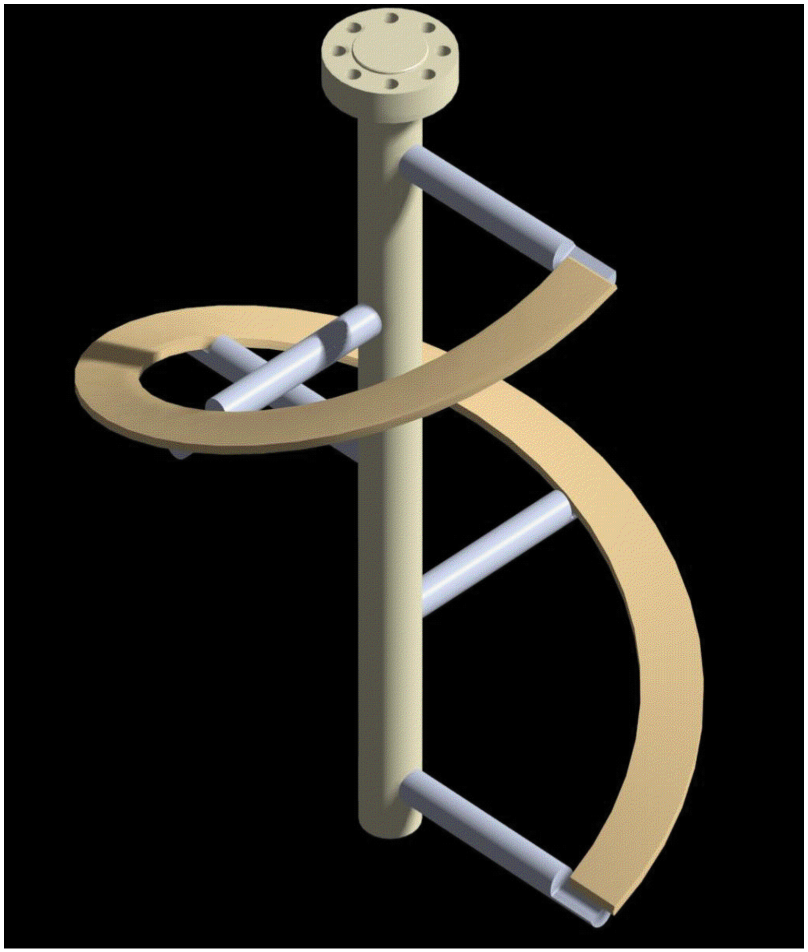
- Design new agitator:
  - Blend time is known.
  - Vessel size is known $\rightarrow$ impeller diameter $\rightarrow$ impeller geometry.
  - Calculate K_P.
  - Calculate $N\theta$.
  - Calculate $N \rightarrow$ check standard speed $\rightarrow$ iterate if necessary.
  - Calculate power draw $\rightarrow$ next standard motor power.

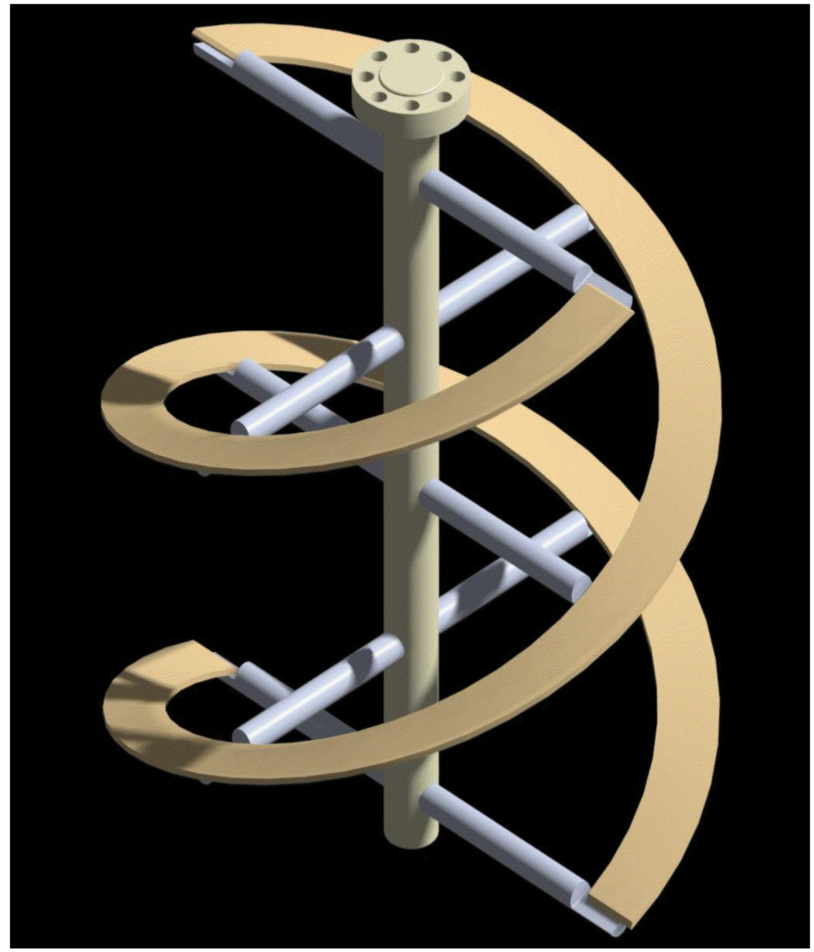
- Rate existing agitator?

Ribbon Nomenclature

- h is impeller height.
- D is impeller diameter.
- n_b is number of ribbons.
- p is impeller pitch.
- c is clearance from wall.

Which Impeller?





Ribbon Selection

- Dual ribbon:
  - Balanced forces on shaft.
  - Higher $K_P \rightarrow$ lower $N\theta$.
- Does lower $N\theta$ result in lower power?
- Shaft diameter may be determined by construction:
  - Must be large enough to have arms welded on safely.

Alternates to Helical Ribbons

- Many exist
- Cheaper to make not better
- May be sensitive to non Newtonian effects

Problem

- Correlations for blend time and power consumption exist for Newtonian fluids.
  - Transitional regime: Blend time proportional to viscosity.
  - Laminar regime: Power proportional to viscosity.
- Many viscous fluids used in industry are non-Newtonian.
- How should rules relating to Newtonian fluids be modified for non-Newtonian ones?

NON NEWTONIAN BLENDING

- To be discussed later

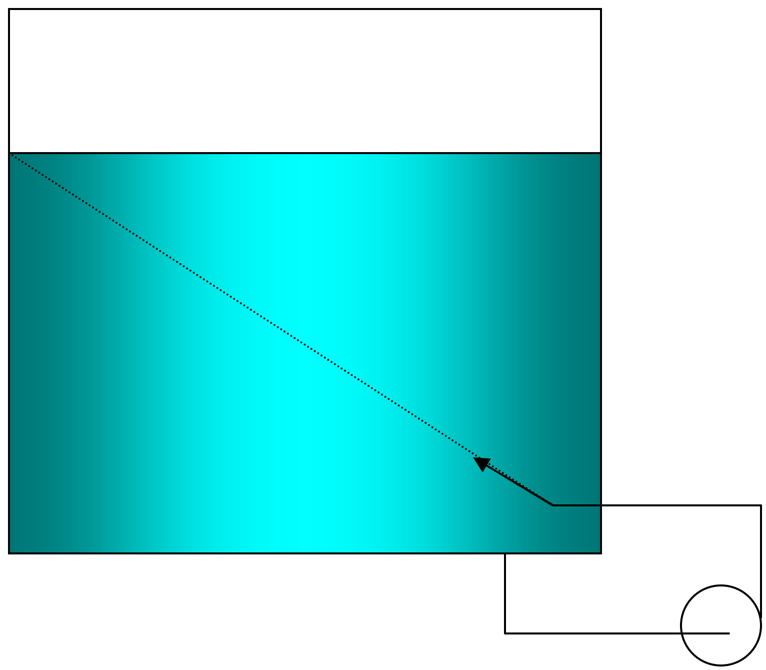
BLENDING WITH JETS

Turbulent jets

MIXING WITH JETS LIQUID

- Jets for tank Mixing
- Maximize path length
- Involve whole tank
- Single jet near bottom
  - no swirl
- Aimed at upper surface a t 2/3 to full diameter
- Remove liquid from near injection point

JET MIXING OF TANKS



MIXING WITH JETS LIQUID

- Mix time correlation

- Mix time to 95 % = 7.0*T^1.5*H^.5
  /Vj / Dj

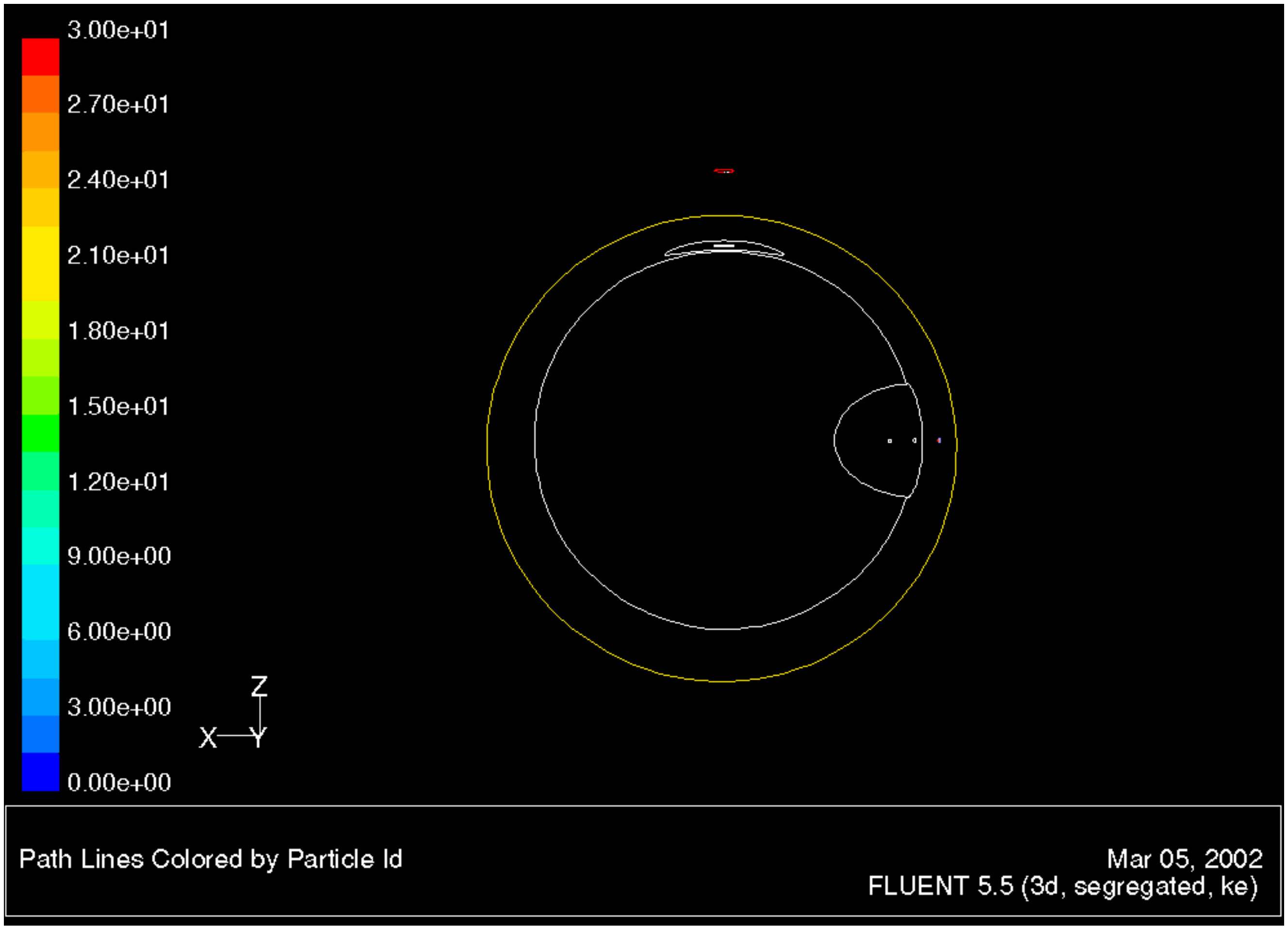
MIX TIME CORRELATION

- Grenville and Tilton
- Use path length
  - Mix time = 3*Z^2/(Vj*Dj)
- For Vj*Dj/Z> .0132 m/sec
- See Handbook of Industrial Mixing 2003 for more details

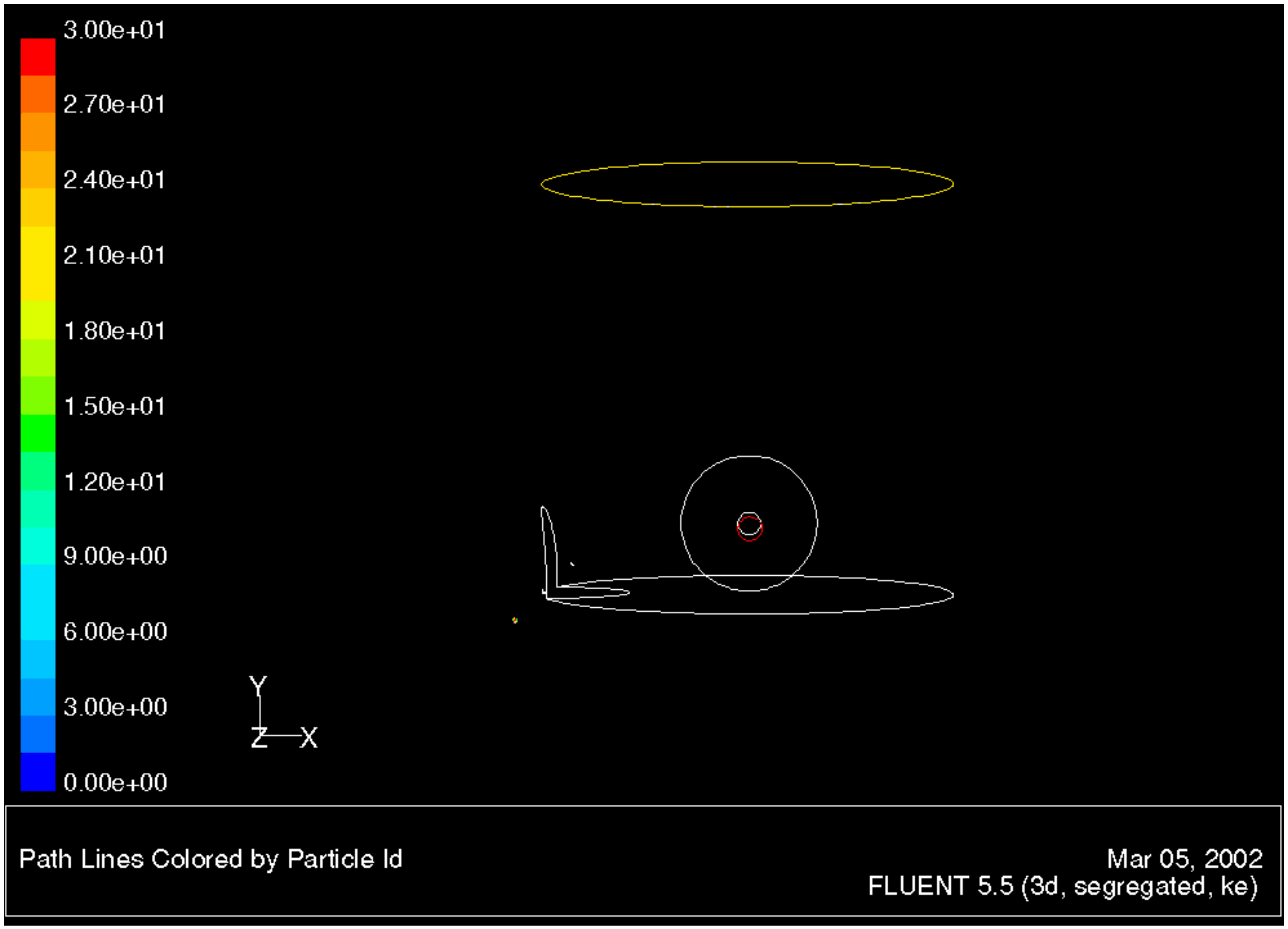
HINTS

- Start with Vj = 10 m/sec – a reasonable velocity
- Expect mix time of the order of minutes to hours roughly proportional to tank diameter rather than the seconds found with mechanical mixer
- Extension into transitional, laminar and non Newtonian flow not easily achieved. Stay above REj=10,000

JET MIXING
CFD – Chris Wolf - Fluent



JET MIXING


3.00e+01
2.70e+01
2.40e+01
2.10e+01
1.80e+01
1.50e+01
1.20e+01
9.00e+00
6.00e+00
3.00e+00
0.00e+00
Y
Z
X
Path Lines Colored by Particle Id
Mar 05, 2002
FLUENT 5.5 (3d, segregated, ke)

HOW FAR CAN THIS BE PUSHED

- Limit of jet action
- See Tilton and Grenville in HIM
- Suggest that jet effectiveness ends when turbulence drops below a certain value.

NOMENCLATURE

- H – liquid height
- Z, z – jet path length
- T – tank diameter or temperature
- Dj – jet diameter
- Q – flow – water, l – liquid, g- gas
- Qj – flow out of jet
- Vj – velocity at jet
- Pm – power per unit mass
- RE – Reynolds Number at jet

END SECTION M5