Fluid Mixing in Biotech and Pharmaceutical Applications

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Agenda

- ***Mixing Theory***
- ***Process Design of Agitators***
  - ***Blending and Motion, Solids Suspension, Gas Dispersion***
  - ***Impellers -- Types and Styles***
  - ***Computational Fluid Mixing***
- ***Agitator Basics***
  - ***Gearbox/Agitator Types***
  - ***Mounting Styles and Seals***
  - ***Mechanical Design of Shafts***
  - ***Information Needed for Specifying an Agitator***
- ***Troubleshooting***
- ***Invited Comment***

What is Fluid Mixing?

- A combination of two or more species through mechanical means to produce a desired result
- A rotating agitator produces high velocity liquid streams which come into contact with stagnant or slower moving liquid, therefore momentum transfer occurs.

Dimensionless Groups

- Mathematical models obeying the laws of conservation of mass and momentum yields a few significant groups applicable to fluid motion
- Will not derive the groups from the Navier-Stokes equation, rather they will be presented and significance explained

Dimensionless Groups - Nomenclature

D	=	Impeller Diameter
T	=	Tank Diameter
N	=	Impeller Rotational Speed
Z	=	Liquid Level Height
:	=	Fluid Viscosity
Sg	=	Fluid Specific Gravity
C	=	Impeller Off Bottom Clearance
S	=	Impeller Spacing

Reynolds Number

- A measure of the ratio of inertial forces (those produced by the agitator) to viscous forces
- N_{Re} = 10.7 N D^2 Sg/:
  (: = cp, D = inches, N = rpm)
- Affects:
  - Power Draw of Impellers
  - Pumping Capacity of Impellers
  - Static Mixer Design
  - Surface Deformation
  - Number of Impellers
  - Baffle Design

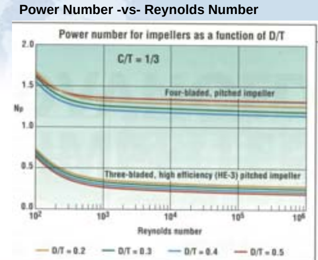
Froude Number

- A measure of the ratio of Inertial to Gravitational Forces
- $N_{Fr} = N^2 D/g = 7.2 \times 10^{-7} N^2 D$
  (N = rpm, D = inches)
- Used in Gas Dispersion and Solids Draw Down Applications
- In many applications, gravitational effects are unimportant and the Froude Number is not significant

Power Number -- N_p

- Dependent upon type/design of impeller and fluid properties
- $N_p = f(N_{Re}, N_{Fr})$
- Oftentimes N_{Fr} is not an effect and for high N_{Re} (Low Viscosity) the power number is constant
- Experiments at different speeds, impeller diameters, and fluid properties shows:
  P % N^3 P % D^5 P % Sg
- The ratio of Power to N,D, & Sg is the Power Number:
  N_p % P/(N^3 D^5 Sg)

Power Number -vs- Reynolds Number



What Affects Power Draw?

- Fluid Properties such as Viscosity and Specific Gravity and (if present) Gas
- Impeller Type, Diameter, Pitch, and Width
- Impeller Rotational Speed
- Geometric Effects such as Baffles, Coils, Liquid Level, Pump Inlets, and Agitator Mounting
- Proximity Effects such as Impeller Diameter to Tank Diameter Ratio and Off-Bottom Clearance
- Plus others to a lesser extent (blade thickness)

Power Draw Calculation

$$Hp = 6.556 \times 10^{-14}\ N^3\ D^5\ Sg\ Np$$

Where:

N = Impeller Speed, rpm
D = Impeller Diameter, inches
Sg = Fluid Specific Gravity
Np = Impeller Power Number

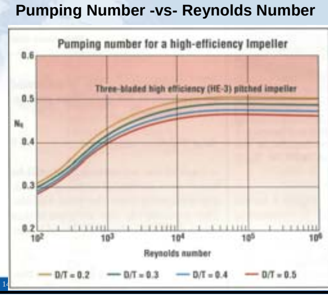
Pumping Number -- N_q

- Dependent upon type/design of impeller and fluid properties
- Flow of impeller is proportional to N & D^3
  Q % N D^3
- The ratio of these two quantities is the Pumping Number, N_q
  $N_q = Q/ND^3$
  $Q = N\ D^3\ N_q$
- $N_q = f(N_{Re})$

What Affects Pumping Rate?

- Fluid Properties: Viscosity, Presence of Gas, Specific Gravity
- Impeller Properties: Type of Impeller, Pitch, Width, Diameter, Clearance, etc.
- Rotational Speed
- Geometric Affects: Tank Diameter, Liquid Levels, Draft Tubes, Baffles, etc.

Pumping Number -vs- Reynolds Number



Pumping Rate Calculation

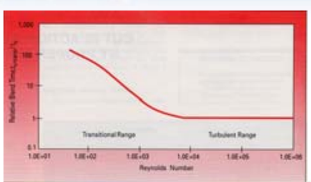
$$Q\ (gpm) = 4.33 \times 10^{-3}\ N\ D^3\ Nq$$

Where:

N = Impeller Rotation Speed, rpm
D = Impeller Diameter, inches
Nq = Impeller Pumping Number

Blend Time

- $T_b = F(N_{Re})$



Blend Time -- Turbulent Flow

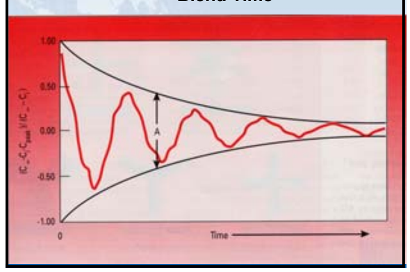
- $t_u = -\ln(1-U)/k$

  Where: t_u = Blend Time for "u" uniformity
  U = % uniformity
  k = Mixing Rate Constant, time $^{-1}$
  (See Advanced Liq. Agitation)

- $k = a\ N\ (D/T)^b\ (T/Z)^{0.5}$

  Where: a = Impeller Constant
  b = Impeller Constant
  N = Impeller Speed, rpm

Blend Time



Blend Time

- For 99% Uniformity

  $t_{99} = 4.605/k$

Degree of Uniformity	Relative Blend Time
90	0.50
95	0.65
99	1.00
99.9	1.50
99.99	2.00
99.999	2.50

Blend Time

- Blend times for higher viscosity fluids (N_{Re} below turbulent) are corrected from a N_{Re} -vs- blend time chart
- Ways to improve Blend Time
  - Do not start from “Stratified” state
  - Introduce additions near impeller
  - Pre-blend with Static Mixers (High Viscosity,Sg, and Volume Ratios)

What determines Agitator Size?

- In simple terms, the size of the agitator gearbox is rated on “Torque”
- Torque is proportional to Hp and Speed

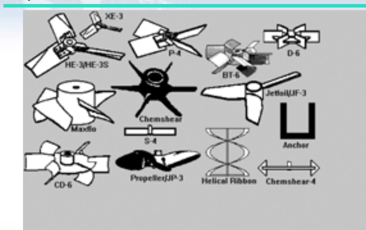
  J % Hp/N
- **J** (in-lbs.) = 63,025 Hp/N

Torque

- 3 hp at 68 rpm ➔ 2,780 in-lbs.
- 10 hp at 100 rpm ➔ 6,302 in-lbs.
- The 10 hp at 100 rpm, would be a size “3” and the 3 hp at 68 rpm unit would be a size “1” agitator
- Relative cost difference is about 40%
- For the same type impellers:

  Higher Torque = Higher Flow = Higher Cost

Impellers



Impeller Styles

- Turbine Style Impellers
  - Axial Flow (High Efficiency)
  - Radial Flow (Straight Blade/Disc)
- Close Clearance Impellers
  - Helix/Anchor
- High Shear
  - Rotor/Stator

Commercial Impellers

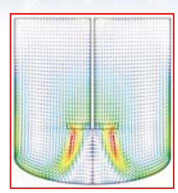
- Following Impellers Show types of Impellers
- Examples of the impellers are from Chemineer
- Other Manufacturers Manufacture similar impeller styles

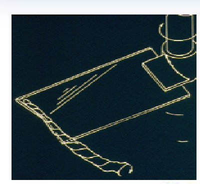
High Efficiency Impeller

- ***Liquid Blending, Solids Suspension, Heat Transfer, Upper Impeller in Gas Dispersion***
- ***Low Shear, High Pumping, Axial Flow***
- ***Reynolds Numbers $100***
- ***Turbulent Np = 0.28 (0.26 - 0.30)***
- ***For a given agitator, the appropriate HE impeller is 20 percent larger than a pitched blade***
- ***Jet Foil Impellers will adhere to similar characteristics***

HE-3 Impeller

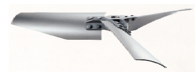
HE-3 Impeller Flow





High Efficiency/Hydrofoil Impeller

- •Liquid Blending, Heat Transfer, Solids Suspension
- •Low Shear, Axial Flow, High Pumping
- •Similar in performance to HE-3
- •Np = 0.55 (0.5 to 0.6)
- •Curved design of blade/hub results in higher strength: lower weight
- •Design requires cast impeller hubs



SC-3 Impeller

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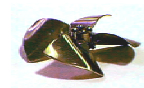
High Efficiency High Solidity Impeller

Np = 0.85 (0.8 to 0.95)

- Wide Blade hydrofoil impeller, axial flow
- Applications which require a high solidity axial flow impeller: three-phase systems, gas dispersion, abrasive solids, transitional flow (100>Nre<2,000)



Maxflo W

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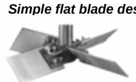
Pitched Plade Impeller

- Liquid Blending, Heat Transfer, Solids Suspension
- Especially good for drawing a vortex or for material drawdown
- Mixed Axial/Radial Flow
- Typical: 4-Blades, W/D = 0.20, 45 degree
- Turbulent Np = 1.3 (1.15 - 1.45)
- Reynolds Number >10
- Simple flat blade design is often economical



P-4 Impeller

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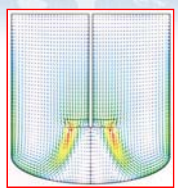
P-4 Impeller Flow



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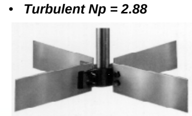
Straight Blade Impeller

- Straight Blade Impeller with four blades
- Liquid blending, keep outlets clear from solids, solids drawdown, tickler@ impeller, immiscible fluid blending
- Reynolds Number >1
- Turbulent Np = 2.88



S-4 Impeller

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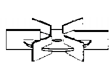
Rushton Turbine

- 6-Bladed Disc Style Impeller
- Gas dispersion at low and intermediate gas rates, liquid-liquid dispersion
- Turbulent Np = 5.0
- Dated Technology



D-6 Impeller

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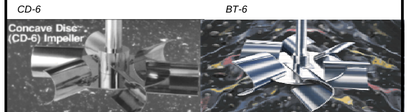
High Efficiency Gas Dispersion Impellers

- 6-Bladed Curved Disc Impeller
- Gas Dispersion at all gas rates
- Fermentations, Liquid/Liquid Dispersions

CD-6

BT-6



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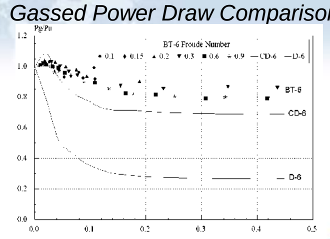
Gassed Power Draw Comparison



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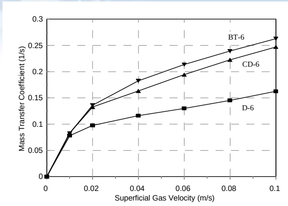
Mass Transfer Coefficient



Retrofit comparison $k_l a$ at $P_u/V = 2.2\ kW/m^3$

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Anchor Impeller

- ***Close Clearance Agitator***
- ***Typical D/T Range: 0.95 - 0.98***
- ***Viscous Liquids (> 100,000 cp)***
- ***Blending and Heat Transfer***
- ***Less efficient but more cost effective than Helical Ribbon***
- ***Less surface area for cleaning than Helical Ribbon***

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Helical Ribbon

- ***Close Clearance Agitator***
- ***Typical D/T range: 0.95 - 0.98***
- ***Viscous Liquids (> 100,000 cp)***
- ***Blending and Heat Transfer***

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System Geometry and Impellers

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Choosing Impellers

•Flow Controlled Processes:
- ***•Blending Miscible Fluids, Heat Transfer, Solids Susp.***
- ***•High Efficiency/Pitched Blade/High Solidity***

•Dispersion Processes
- ***•Gas Dispersion, Immiscible Fluids***
- ***•Radial Flow Impellers***
- ***•Combination: Lower Radial (Disk)/Upper Axial***

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Impeller Performance - Example

High Pumping/Low Shear

HE-3
JF3
SC-3
Maxflo W
P-4
S-4
BT-6
CD-6
D-6
Rotor/Stator Low

Pumping/High Shear

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Impeller Performance

•Buffer Tanks, Blend Tanks, Heat Transfer, Solids Susp.
- • High Efficiency Impellers

• Reactors:
- • High Efficiency Impellers
- • Gas Dispersion Impellers
- • Pitched Blade Impellers
- • Helix (High Viscosity)

• Solids Drawdown
- • Pitched Blade Impellers

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Impeller Design Options

- All welded impellers
- Threaded/sealed impellers
- Bolted (acorn nuts) blades
- Set Screws, Keys, other options available

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Geometry

- Number of impellers depends on
  - Type of impeller
  - Viscosity/Reynolds Number of fluid
  - Liquid Level to Tank Diameter Ratio (Z/T)
- Impeller Diameter/Tank Diameter (D/T Ratio):
  - Affects Power Number of Impeller
  - Large D/T ratios not advised for Solids Susp.
- Location
  - For low level mixing, “tickler” impeller used

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Baffles

- Baffles are used to prevent swirling in lower viscosity applications and promote "top to bottom" mixing.
- Baffled Tanks produce the best mixing results
- Baffling not required in angled or vertical off center mixing
- In certain situations, special baffle configurations may be used. Examples include vortex induction, baffles with internal fluid flow for heat transfer capability

Recommended Baffling

Reynolds Number	Baffles
$N_{Re} > 1{,}000$	T/12 width, T/72 offset
$500 < N_{Re} < 1{,}000$	T/24 width
$N_{Re} < 500$	None

- Number and spacing dependent upon impeller types

Where: T = Tank Diameter

Impeller Equations

- Primary Pumping Capacity
  - Q (gpm) = 4.33×10^{-3} N D^3 Nq
- Impeller Horsepower Draw
  - P = 6.556×10^{-14} N^3 D^5 Sg Np
- Impeller Reynold's Number
  - N_{Re} = 10.7 N D^2 Sg / :

Where: N = Rotational Speed, rpm
D = Impeller Diameter, inches
Nq = Impeller Pumping Number
Np = Impeller Power Number
Sg = Fluid Specific Gravity
: = Fluid Viscosity, cp

Impeller Summary

- Many different impeller styles available
- Agitator design starts with impeller selection
- Need to match impeller performance with process requirements as impeller efficiency can affect agitation.
- High efficiency impellers can improve agitation for a given torque by generating a more uniform, axial flow pattern
- Special impellers such as the BT-6 improve gas handling.
- Wide blade hydrofoils (Maxflo W) are very good in 3-phase flow and as pumping impellers above a gas dispersion impeller.

Mixing Classifications

- **Blending and Motion**
- Solids Suspension
- Gas Dispersion

Blending and Motion

- Liquid in contact with another liquid
- Examples:
  - Liquid – Liquid Reactions
  - Blending of Miscible Liquids
  - Heat Transfer Improvement
  - Blending out Dissimilarities
  - Low Solids Slurries (< 2% Solids)

Problem Magnitude

- Size
- Difficulty
- Process Result/Dynamic Result

Blending and Motion

- Size
  - Equivalent Volume
  - V_{eq} = Volume Sg
- Difficulty
  - Fluid Viscosity
- Process Result/Dynamic Response
  - Process Results are related to Flow Rate

Determining Process Requirements

- How much flow is needed for the process?
  - Specific Blend Times
  - Batch Times
  - Heat Transfer Requirements
  - Components being mixed

Determining Process Requirements

- It is difficult to state the process result with precision. Such as how do you relate flow rate and blend time to:
  - Design of a pH adjustment tank?
  - A Chemical Reaction?
  - Blend two very dissimilar components?

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Blending and Motion Design

- Fundamental Dynamic Response for Blending and Motion is:
  - Bulk Fluid Velocity
    - Characteristic of all velocities in the agitated fluid
- Design logic starts with the selection of a "Dynamic Response"
- Design Agitators to produce that response

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Determining Process Requirements

- Bulk Fluid Velocity Calculation:

v (ft/min) = Q (ft^3/min) / A (ft^2)

where:
v = Bulk Fluid Velocity
Q = Flow Rate
A = Cross Sectional Area of Tank

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Determining Process Requirements

- Experience has shown the majority of Blending and Motion problems are solved with Bulk Fluid Velocities of 6 to 60 ft/min
- It is then possible to assign "Agitation Intensity Levels" to these Velocities
- Chemineer calls these levels "ChemScale"

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Blending and Motion

Bulk Fluid Velocity	ChemScale Level
6 – 60 ft/min	1 to 10

- The lower the intensity level, the lower the characteristic velocity, the lower the flow rate, and the smaller the Agitator
- ChemScale Levels can be used to describe Process Results in more detail, which is called a Dynamic Response

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MILD AGITATION Agitation levels 1 and 2 are characteristic of applications requiring minimum fluid velocities to achieve the process result.

Scale of agitation	*Bulk fluid velocity, ft/min*	*Description*
1	6	Agitators capable of level 1-2 will:
		Blend miscible fluids to uniformity if the specific gravity differences are less than 0.1.
2	12	Blend miscible fluids to uniformity if the viscosity of the most viscous is less than 100 times that of the other.
		Establish complete fluid-batch control.
		Produce a flat, but moving surface.

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MEDIUM AGITATION **Agitation levels 3-6 characteristic of fluid velocity in most chemical process industries**

Scale of agitation	*Bulk fluid velocity, ft\min*	*Description*
3	18	Blend miscible fluids to uniformity if specific gravity differences are less than 0.3 (Scale 3) and 0.6 (Scale 6)
4	24	Blend miscible fluids to uniformity if the viscosity of the most viscous is less than 5,000 (Scale 3) or 10,000 (Scale 6) times that of the other.
5	30	
		Suspend trace solids (<2%) with settling rates of 2 to 4 ft/min.
6	36	Produce surface rippling at lower viscosities

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VIGOROUS/VIOLENT AGITATION **Agitation levels 7-10 characteristic of applications requiring high fluid velocity for the process result, such as critical reactors**

Scale of agitation	*Bulk fluid velocity, ft/min*	*Description*
7	42	Blend miscible fluids to uniformity if Sg differences are less than 0.7 (Scale 7) or 1.0 (Scale 10).
8	48	Blend miscible fluids to uniformity if the viscosity of the most viscous is less than 70,000 (Scale 7) or 100,000 (Scale 10) times that of the other.
9	54	Suspend trace solids (<2%) with settling rates of 4 to 6 ft/min.
10	60	Provide surging surfaces at low viscosities.

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Example

Application	ChemScale
Media Prep Tank	1-2
Resin Prep Tank	1-2
Buffer Prep Tank	1-2
pH Adjustment	1-3
Reactor	6-10
Blend Tanks	4-7
Solids Dissolving	3-5

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Blending and Motion

- Solving Blending and Motion problems also requires the selection of the optimum impeller type
- Impellers will produce a combination of flow and shear (or head)
- For Blending and Motion, increasing flow and decreasing shear is typically most desirable
- High Efficiency Impellers are used most often

Agitator Selection

- Process involves
  - Pick Impeller Type
  - Determine Size and Difficulty
  - Determine Dynamic Response (ChemScale Level)
- Charts will provide Hp/Speed Combinations which when loaded properly will provide the Flow to produce desired Bulk Fluid Velocity and hence Agitation Level desired

Blending and Motion

- For a particular Hp/Speed Combination (Torque Level) the final steps are:
  - Choose Impeller Diameter to draw the defined hp
  - Check geometric parameters D/T, C/T, Z/T
  - Check other process parameters (Blend Time, Heat Transfer Rate, etc.)
  - Mechanical Design (Gearbox, Shaft, Seal, etc.)

Blending and Motion

- Last step is Economic Evaluation
  - Capital Cost Estimation
  - Operation Cost Estimation
  - Optimization
- Luckily, the calculations are computerized and a process and mechanical design can be done quickly

Evaluating Agitation

- ***Motor hp does not correlate directly to mixing performance***
- ***Torque correlates better with mixing intensity (Chemscale)***
- ***Why? For low horsepower and low speed combinations, a large impeller is utilized. Flow is proportional to N D³.***
- ***Torque relates to capital cost. Motor hp relates to operating cost. Consider both when considering agitator purchase!***

Mixing Classifications

- Blending and Motion
- **Solids Suspension**
- Gas Dispersion

Solids Suspension

- Liquid in contact with Solids
- Examples:
  - Catalytic Media Suspension
  - Solids Incorporation
  - Resin / Buffer / Media Prep tanks (depending on specific process)

Solids Suspension

- Solids suspension applications, like Blending and Motion problems, are "Flow Controlled"
- This leads us to use "Flow" impellers rather than "Shear" (or head) impellers
- High Efficiency Impellers are used most often
- High Efficiency Impellers also reduce particle shearing

Solids Suspension

- Design Procedure
  - Size
  - Difficulty
  - Process/Dynamic Response

Solids Suspension

- Size
  - $V_{eq} = V \ \ Sg_{sl}$

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Difficulty Parameter

- Design Settling Rate:
  f (TSR,)Sg, Sg_L Fw)

  Where: TSR = Terminal Settling Rate
)Sg =) Specific Gravity between solids and liquid
  Fw = Weight Percent of Solids
  Sg_L = Specific gravity of Liquid

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Process Result/Dynamic Response

- There are (4) levels of Suspension
  - No Solids Motion
  - Solids Motion on Bottom
  - Complete Suspension
  - Complete and Uniform Suspension

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Design Procedure

- Calculate settling velocity from solids and liquid properties or measure experimentally
- Calculate Njs (Just-Suspended Speed) based on TSR, Impeller, Geometry --D/T, etc.
- If N > Njs => Complete Suspension
- Calculate Cloud Height or % "Unsuspended"

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Design Procedure

$$N_{js} = k\left[\left[\frac{(\rho_s - \rho_l)}{\rho_l}\right]u_t\right]^{0.28} * f(X) * f(D/T) * (T/T_o)^{-n}$$

Where:

k	=	Impeller Constant
D_s	=	Solids Density
D_l	=	Liquid Density
u_t	=	Terminal Settling Velocity
f(X)	=	Solids Loading (%) factor
T_0	=	Reference Tank Diameter
T	=	Actual Tank Diameter
D	=	Impeller Diameter
n	=	Scale up exponent

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Design Procedure

- Parameters which Change Answers
  - Particle Size & Shape
    - Larger particles have higher settling velocities and require more torque to suspend
    - Icicle-Like or unusual shapes increase difficulty
  - Liquid Viscosity
    - Higher Viscosity hinders settling and makes suspension easier
- Problem of Particle Size
  - Particle size distribution is important information to design optimum unit

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Related Topics

- Makedown: System Specific. May Need High Chemscale and Upper Pitched Blade Impeller for Fine, Difficult to Wet Solids.
- Resuspension: Ranges from Easy to Impossible
- Solid Particle Shearing:
  - High Efficiency Impellers are best

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Solids Suspension Summary

- (3) Levels of mixing
  - Solids Motion
  - Complete Suspension
  - Uniform Suspension
- Calculate N_{js}, Cloud Height
- High Efficiency Impellers are used

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Mixing Classifications

- Blending and Motion
- Solids Suspension
- **Gas Dispersion**

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Gas Dispersion

- Liquid in contact with Gas
- Examples:
  - Aeration Tanks
  - Fermentation
  - BioReactors

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Gas Dispersion

- Gas Dispersion applications, unlike Blending & Motion and Solids Suspension, are "Shear Controlled"
- This leads us to use "Shear" (or head) impellers
- Disc Impellers are most often used (high gas flow).
- Flow impellers can be used in low gas flow applications
- Flow impellers are used as upper impellers in Gas Dispersion Applications

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Design Procedure

- Size
- Difficulty
- Process Result/Dynamic Response

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Gas Dispersion

- Size
  - $V_{eq} = Sg_L\ V$
- Difficulty
  - Actual Gas Flow Rate
- Process Result/Dynamic Response
  - Mass Transfer, kla
  - Break gas into smaller bubbles to increase surface area

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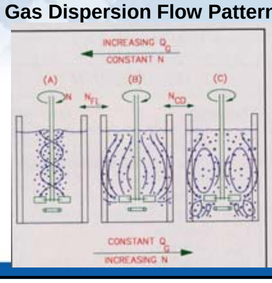
Gas Dispersion Flow Patterns



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Gas Dispersion Flow Patterns

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Gas Dispersion Flow Patterns

- In Turbulent Regime the Flow Pattern depends on:
  - Aeration Number
    - $N_A = Q_g/ND^3$
    - $N_A = 1728\ \ ACFM/(N\ \ D^3)$
  - Froude Number
    - $N_{Fr} = N^2D/g$
    - $N_{Fr} = 7.2 \times 10^{-7}\ \ N^2\ \ D$

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Gas Dispersion

- For a "Completely Dispersed" flow pattern:

  $N_{A,CD} = C_{CD}\ \ (D/T)^{0.5}\ \ (N_{FR})^{0.5}$

  where: C_{CD} is impeller dependent (0.2 for D-6 and 0.4 for CD-6)

  Increasing speed above this point will not change the flow pattern, but will improve gas hold-up and mass transfer

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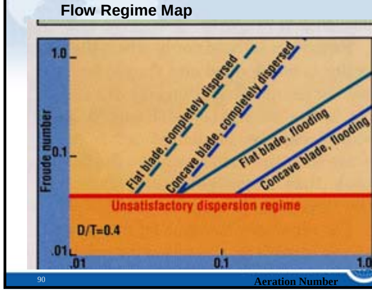
Flow Regime Map



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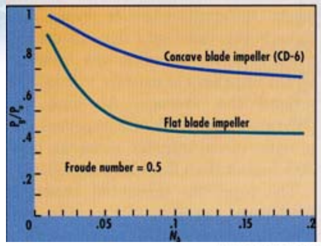
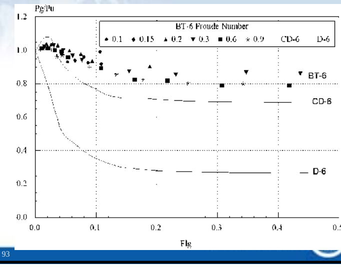
Gas Dispersion

- Power Requirements
  - Power draw will drop when impeller is "gassed"
  - Typically referred to as: Pg/Po
  - Designing agitator for the "gassed" state will yield better results, but need to account for low or no gas situations
  - ACVF Drives

Gas Dispersion -- Pg/Po Curve



Gas Dispersion -- Pg/Po Curve



Gas Dispersion -- Hold-Up

- Gas Hold-Up
  - As gas is dispersed, the liquid level will rise to varying degrees. Must account for this in vessel design
  - Typically an increase in hold-up signifies smaller gas bubbles, thereby increasing surface area, and increasing mass transfer

    " = C ".$(P_g/V_l)^A$ $(v_g)^B$

    Where: " = Gas Hold-Up

    v_g = Superficial Gas Velocity

    C ", A, B = Constants

Design Procedure

- First step is to design the agitator so the impeller is not "Flooded"
- Above flooding, increasing the gas rate will increase kla (mass transfer coefficient):

  kla % $(P_g/V)^a$
- Increased power input will increase mass transfer in the system

Design Procedure

- Determine specific Mass Transfer Rate based on process
- Calculate economical combination of power consumption and gas rate to satisfy the process demands
- Optimization in pilot plant and then scale-up is often times used

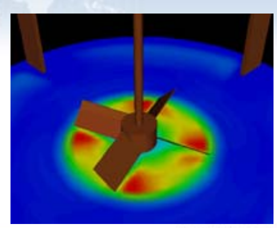
Gas Dispersion -- Impellers

- A lower Dispersion Impeller is commonly used to disperse gas and this impeller is "Concave"
- Using Concave impellers improves the kla becaue it pumps more than flat blade disks, which helps minimize "Coalescence"
- The gas is often introduced through a sparge ring located directly under the impeller
- Recent designs include upper "Flow" impellers particularly in biological systems to:
  - Maintain more uniform dissolved-oxygen concentrations which is important in fermenters
  - Provide excellent overall tank blending

Gas Dispersion Summary

- Choosing the correct impeller system to avoid "flooding" important
- Higher P/V levels improve performance
- Impeller "Unloading" in gassed –vs- ungassed state needs to be accounted for
- Gas Sparge System Design is important to performance of gas dispersion system
- Computational Fluid Design (CFD) can aid in agitator design

Computational Fluid Dynamics



CFD: Setting Expectations

What To Expect

- Trends
- Visualization
- Complements physical modeling.
- Comprehensive data not easily obtainable from experimental tests.
- Answers for "what if…?" questions.
- Highlights the cause not just the effect.

What Not To Expect

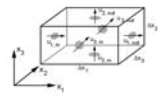
- Replacement for good engineering judgement
- Complete replacement for testing
- Accurate results require
  - Detailed models
  - Knowledge of your problem
  - Knowledge of limitations

How CFD will help you

- CFD predicts the flow field that rules the process.
- CFD predicts performance in meeting the intended task: blending time, mixing time scales, heat transfer coefficients, etc.
- Many different impeller styles can and have been analyzed.

Computational Fluid Dynamics

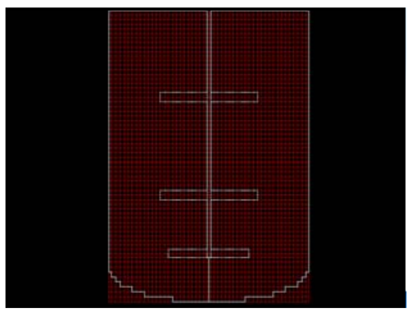
- The fluid flow domain is subdivided into a large number of computational cells. This is called the mesh or grid.
- Solve the mathematical conservation equations for:
  - mass
  - momentum
  - energy
  - turbulence
  - chemical species



- Results:
  - detailed flow and shear fields
  - temperature fields
  - chemical concentrations and productivity
  - local mass fractions of additional phases

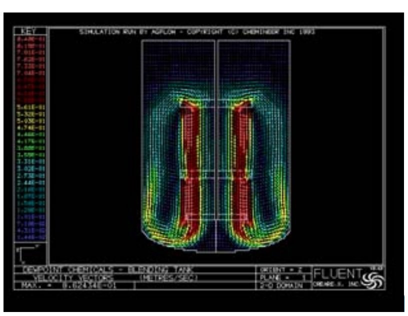
The CFD Process

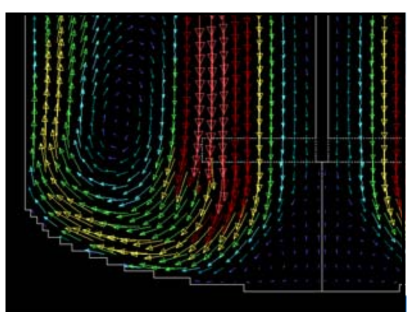
- Determine agitator design you want to simulate

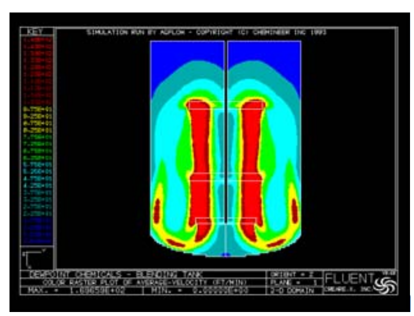


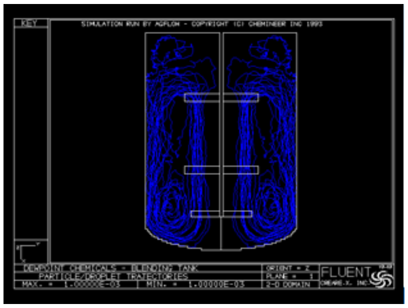
CFD

- Boundary conditions are experimentally established for impeller (LDV, DPIV)
- 2-D runs use a k-, model to solve equations in turbulent flow
  - k = Kinetic Energy of Turbulence
  - , = Rate of Dissipation of Turbulence
- Results will produce a time averaged flow profile

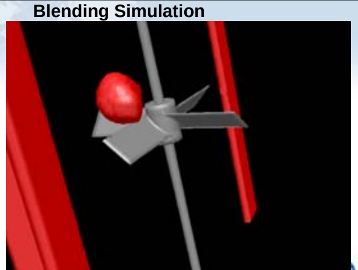








Blending Simulation



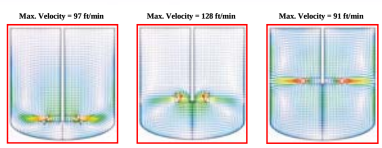
Why look at flow patterns?

- Flow patterns influence
  - Blend time
  - Level of solids suspension
  - Overall inside heat transfer coefficients
  - Distribution of dissolved O_2 in fermentations
  - Suspension of solids in the tank heel
  - Selectivity in competitive/competitive consecutive reactions
- Flow patterns can be affected by:
  - Impeller style
  - Impeller to tank diameter ratio
  - Relative off-bottom distance
  - Viscosity (Reynolds number)
  - Impeller spacing

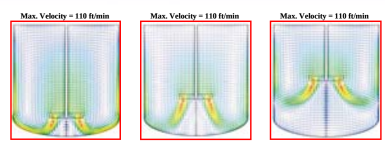
ENGINEERING PHARMACEUTICAL INNOVATION ISPE

Flow Patterns at Different Impeller Off Bottom Clearances

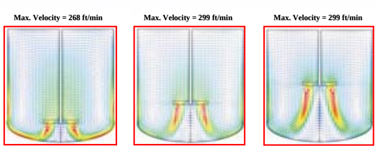
S-4 Impeller, Turbulent Flow, Constant Torque, D/T=1/3



P-4 Impeller, Turbulent Flow, Constant Torque, D/T=1/3



HE-3 Impeller, Turbulent Flow, Constant Torque, D/T=1/3



Observations at Different Impeller Off Bottom Clearances

- Radial Flow Impeller: S-4
  - Characteristic 2 cell system at all clearances
  - Proportionally more flow to lower cell at intermediate clearances
- Mixed Flow Impeller: P-4
  - Set up large lower cell at high clearances
  - Flow in lower cells fraction of upper
- Axial Flow Impeller: HE-3
  - Conical area below impeller grows with clearance
  - Flow pattern hits bottom even at high clearances

Summary

Flow patterns can be affected by:

- Impeller style
- Impeller to tank diameter ratio
- Relative off-bottom distance
- Viscosity (Reynolds number)
- Impeller spacing

CFD Conclusion

- CFD can be used to analyze:
  - Laminar blending
  - Turbulent blending
  - Stirred tank flow patterns
  - Optimize impeller designs
  - Laminar and turbulent flow static mixers
  - Heat transfer
  - Mass transfer
  - And many other mixing applications such as fluidized beds, bubble columns, etc

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Basic Components

- ***Agitator Drive – Speed Reducer***
- ***Prime Mover – Motor***
- ***Drive Mount/Shaft Seal***
- ***Mixer Shaft***
- ***Impeller(s)***

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Agitator Drives

Types
- ***Built by Agitator Manufacturer***
- ***Buy-Out with Modifications***
- ***Buy-Out***

Configuration
- ***Right-Angle***
- ***Parallel/Inline***
- ***Portable/Clamp***

Gearing
- ***Spiral Bevel***
- ***Helical***
- ***Other (worm, planetary, etc.)***

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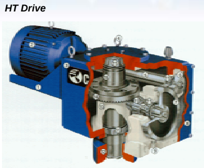
High Torque Gear Drives

HT Drive



- ***Up to 1,000 hp***
- ***Spiral Bevel & Helical Gearing***
- ***Tailored to large applications***
- ***FDA White or Steel-It Paint***

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Medium Torque Gear Drives

GT Drive

- ***1 to 30 hp***
- ***11 to 155 rpm***
- ***Helical Gearing***
- ***Adaptable to wide application ranges***
- ***FDA White or Steel-It Paint***

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Low Torque Drive Typical Features

- ***Right Angle or Parallel***
- ***Various Gearing Options***
- ***1/4 to 5 hp***
- ***350 rpm standard***
- ***Customized speeds available***
- ***Equivalent to Chemineer DT, RBT, BT***

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Basic Components

- ***Gear Drive – Speed Reducer***
- ***Prime Mover – Motor***
- ***Drive Mount/Shaft Seal***
- ***Mixer Shaft***
- ***Impeller(s)***

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Prime Mover

Electric Motor -

Foot Mounted / C-Face Mounted

TEFC / FCXP

Standard / Chemical / Washdown Duty

ACVF Drives – Variable Speed

Air Motors

Other Drives - Hydraulic, Engines

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Basic Components

- ***Gear Drive – Speed Reducer***
- ***Prime Mover – Motor***
- ***Drive Mount/Shaft Seal***
- ***Mixer Shaft***
- ***Impeller(s)***

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Mounting Configurations

- *Pedestal Mounted*
  - *Lip Seal (Low Pressure – 2 to 3 psi)*
  - *Mechanical Seals*
    - *Single Seals – Up to 150 psi*
    - *Double Seals – Maximum pressure range*
- *Flange Options*
  - *Ferrule (tri-clamp)*
  - *ANSI*
  - *DIN*

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THINGS TO CONSIDER ABOUT AGITATOR MOUNTING

- *Weight*
- *Torque*
- *Bending Moment*
- *Seal Requirements*
- *Entry Point of Shaft*

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Agitator Seals

Mechanical Seals

- *Types*
  - *Single/Double*
  - *Lubricated/Dry Running*
- *Manufacturers*
  - *Flowserve*
  - *John Crane*
  - *Chesterton*

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Agitator Seals

Single Mechanical Seals

- *Single Mechanical Seals*
- *Leak path is to the atmosphere*
- *Lower leakage rates than stuffing boxes*
- *Suitable to 150 psi*
- *Typically Dry Running*
- *Carbon -vs- Tungsten Carbide/Viton/316ss*
  - *Optional Materials*
    - *Silicon Carbide/Kalrez/EPDM/Teflon/Higher Alloys*

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Agitator Seals

Double Mechanical Seals

- *Leak Path is into vessel*
- *Lowest Leakage Rate*
- *Chemineer uses a "back to back" arrangement (Pressurized Cartridge)*
- *Often requires liquid lubrication*
- *Carbon -vs- Tungsten Carbide/Viton/316ss*
  - *Options: Silicon Carbide/ Kalrez/ EPDM/ Teflon/ Alloys*

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Basic Components

- *Gear Drive – Speed Reducer*
- *Prime Mover – Motor*
- *Drive Mount/Shaft Seal*
- *Mixer Shaft*
- *Impeller(s)*

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Shaft Design

- *Shaft Stresses (Shear/Tensile)*
- *Shaft Critical Speed*
- *Materials of Construction*

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DESIGN FOR SHAFT DIAMETER

- *FOLLOW PROCESS/IMPELLER DESIGN*
- *SELECT SHAFT LENGTH*
- *DETERMINE THE MINIMUM REQUIRED SHAFT DIAMETER FOR STRESSES*
- *CALCULATE SHAFT CRITICAL SPEED*
- *COMPARE CRITICAL SPEED RATIO TO ALLOWABLE VALUE*
- *ITERATIVE PROCESS*

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ALLOWABLE SHAFT STRESS

SHEAR STRESS= 6,000 PSI S_F (TWISTING)

TENSILE STRESS= 10,000 PSI S_F (ELONGATION)

S_F = STRESS FACTOR (MATERIAL AND TEMPERATURE DEPENDENT)

316ss = 1.0
304ss = 0.95
C276 = 1.33

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SHAFT CRITICAL SPEED CRITERIA

- *Critical Speed*
  - *•rotation speed corresponding to a natural frequency of a shaft/impeller system*
- *First Critical Speed*
  - *•Most Important*
- *Agitator Designs Operating Below the first critical speed (lowest) are optimal*
  - *•Low torque designs can be designed to run > critical*

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CRITICAL SPEED RULES

NON-STABILIZED IMPELLER

Pitched/Straight Blade	*65%*
High Efficiency	*80%*

STABILIZED IMPELLER

Pitched/Straight Blade	*80%*
Well Designed HE	*NOT REQUIRED*

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CRITICAL SPEED CALCULATION

$$N_c = \frac{0.394\ 10^6\ d^2\ F_M}{L \sqrt{W_e} \sqrt{(L + S_b)}}$$

W_e = *Equivalent Weight*
L = *Shaft Length*
S_b = *Bearing Spacing*
$d.$ = *Shaft Diameter*

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Critical Speed Options

- *Increase Shaft Diameter*
- *Shorten Shaft: A few inches has a pronounced effect, but need to maintain process performance*
- *Choose Lower Power/Lower Speed Agitator*
- *Remove Weight*

•Step the Shaft
•Reduce blade thickness

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Materials of Construction

- ***Carbon Steel***
- ***Stainless Steels***
  - ***304/304L***
  - ***316/316L***
  - ***Duplex (AI6XN / Ferralium / Avesta 254)***
- ***High Nickel***
  - ***Alloy 20***
  - ***Alloy 200***
  - ***Alloy C276/B2***
- ***Others***
  - ***Monel 400 ---- Inconel 600/625/800***
  - ***Titanium***

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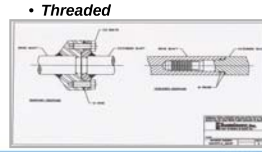
Shaft Couplings

- ***Non-Sanitary***
  - ***Welded/Bolted***
- ***Sanitary***
  - ***Welded/Acorn Nuts***
  - ***Threaded***



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Basic Components

Gear Drive – Speed Reducer
Prime Mover – Motor
Drive Mount/Shaft Seal
Mixer Shaft
Impeller(s)

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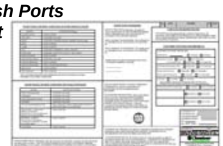
Additional Design Considerations

- ***Surface Finish Requirements***
- ***Rounded Edges / Smooth Welds***
- ***USP Class VI or FDA elastomers***
- ***Debris Well / Flush Ports***
- ***Beveled Washout***



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Information for Agitator Design

- ***Type of Data***
- ***Vessel Data***
- ***Process Data***
- ***Mechanical Data***
- ***Previous Experience***
- ***Documentation Requirements***
- ***See Agitator Data Sheet for typical required data***

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Vessel Data

- **Dimensions**
  - *Diameter, Straight Side, Mounting Height, Top and Bottom Depths, Agitator Mounting Flange Size, Access Way Sizes*
- **Ratings**
  - *Pressure and Temperature*
- **Internals**
  - *Baffles (Chemineer will recommend)*
  - *Cooling/Heating Coils*
  - *Other Obstructions*

Process Data

- **Blending and Motion**
  - *Liquid Properties: Viscosity, Specific Gravity*
  - *Additions to be made and quantities*
  - *Heat Transfer properties (if required)*
- **Solids Suspension**
  - *Liquid Properties: Viscosity, Specific Gravity*
  - *Solids Properties: Particle Size, Sg, Weight %*
- **Gas Dispersion**
  - *Temperature/Pressure of incoming gas*
  - *Gas flow rates*
  - *Liquid viscosity*
  - *Mass Transfer Requirements*

Process Data

- ***Viscosity is most important for Blending and Motion and has greatest influence on agitator sizing***
- ***Solids(Size,%,Sg)/Liquid(Viscosity, Sg) Data is most important for Solids Suspension***
- ***The more accurate the data, the more optimized the agitator***

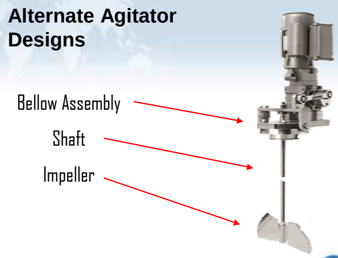
Mechanical Data

- ***Materials of Construction for wetted parts***
- ***Sealing Requirements***
- ***Mounting Requirements***
- ***Other Special Requirements***
  - *Motor Requirements*
  - *Polishing*
  - *Shaft Couplings*

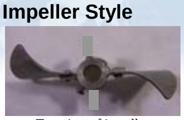
Information for Agitator Sizing Conclusion

- *Specifying/Describing the problem is critical*
- *Accurate data = Accurate Designs*
- *Viscosity is most important parameter on agitator size for Blending & Motion*
- *Sealing, Materials, and other requirements affect the mechanical design of the agitator*
- *Follow Baffle or Mounting recommendations*
- *Many drive types and products to choose*
- *Balance Cost, Features, Benefits, & Service*

Alternate Agitator Designs

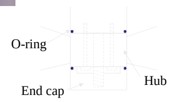


Impeller Style



Top view of impeller

The impeller is designed to convert the rocking motion of the drive to flow with a circumferential component



Sanitary removable impeller design could be an option

Sweeping Blade – New Approach

Eliminates:

- **Particle generation**
- **Rotating mechanical seals & maintenance**
- **In-Tank bearings used with bottom entry mixers**
- **Tank damage associated w/ decoupling of magnetic mixing impellers and/or bearing failures**

Sweeping Blade Addresses:

- **Zero contamination from wearing parts**
- **Easy to clean with few crevices.**
- **Complete Draining.**
- **Zero leakage through seals.**
- **Effective mixing (usually low shear) without baffles.**
- **10:1 turndown w/out avoidance range.**
- **Low center of gravity to avoid top heavy tank/mixer configurations.**
- **Ability to produce very small batches.**
- **Small footprint.**
- **Lower Cost of ownership**

Summary

- The Sweeping blade configuration can effectively address the mixing and mechanical requirements of your systems
- Total cost of ownership is lower than traditional rotating mixers
- Design flexibility to match your needs
- Can retrofit top or bottom entry mixers

Questions?