Optimizing Mixing Applications for Water and Wastewater

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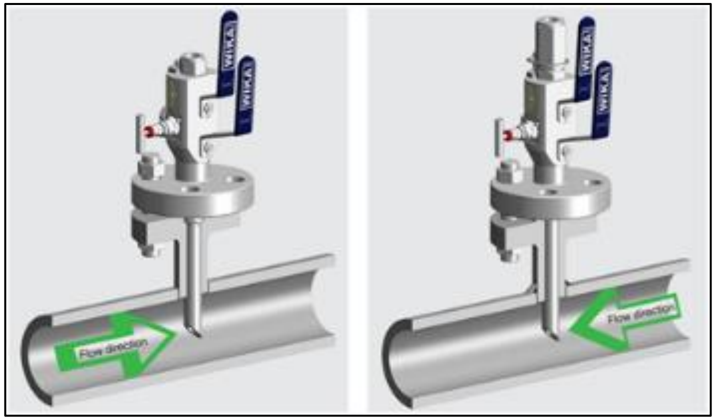
OTCO 60th Anniversary Workshop

July 25, 2024

Agenda

- Review mixing concepts
- Optimum mixing characteristics
- Mixing designs
  - Pipe mixing
  - Static mixers
  - Weir mixing
  - Pump mixers
  - Rapid mixers
  - Vertical or horizontal flocculators
- Questions



Mixing Concepts

- Rapid dispersion of chemicals into water (or wastewater) stream
  - Better distribution of chemical application
  - Fewer byproduct formations
  - Assure chemical interfaces with particulate (or biological) matter
  - Assure chemical interfaces with inorganic contaminants
- G value relationship to process control
  - Step-by-step procedures to determine process design parameters
  - G value and Gt calculations
  - Head loss creates mixing intensity
  - Impeller design criteria

Mixing Concepts

- Detention or reaction time
  - Time required for specific chemical reaction or development of settleable particles

- Generally accepted equation

$$d_t = \frac{V}{Q}$$

  - d_t = detention or reaction time
  - V = basin volume, gallons
  - Q = fluid flow rate, (gpm, gph, gpd, etc.)

Mixing Concepts

- Mixing Intensity (G Value)
  - Smoluchowski develop flocculation kinetics concepts 1916
    - Mathematics Theory for Coagulation and Colloidal Kinetics Using Laminar Flow Conditions and Brownian Movement
  - Camp and Stein (1943) applied turbulent flow conditions to theories for G value concepts
  - Camp (1953) extended practical use of G values and developed Gt concept for flocculator design
  - Kawamura (1981) extended Gt concepts to mixing design
    - Possible to improve mixing by altering detention or reaction time

Mixing Concepts

- Mixing Intensity (G value)
  - Calculated using basin configuration and mixer characteristics
  - G value (Camp and Stein 1943)
  - Later researchers further define power input (*P*) for mixing

$$G = \sqrt{P / \mu V}$$

$$P = \frac{N_p n^3 D^5 \rho}{g}$$

μ - dynamic viscosity
V - basin volume, ft^3
P - power input, ft-lbs/sec
N_p - impeller power number

n - rotational speed, rps
D - impeller diameter, ft.
ρ - water density (temp.)
g - gravitational constant (32.174)

Mixing Concepts

- Mixing intensity (G value)
  - Researchers also defined input power (*P*)
    - Paddle mixers

$$G = \sqrt{\frac{C_d A \sigma v^3}{2 g V \mu}} \qquad P = \frac{C_d A \sigma v^3}{2g}$$

C_d - drag coefficient (1.8 for paddles)

A - cross-sectional area of paddles, ft^2

σ - specific weight of water, lbs./ft^3 (temp)

υ - relative velocity between paddles and water, fps

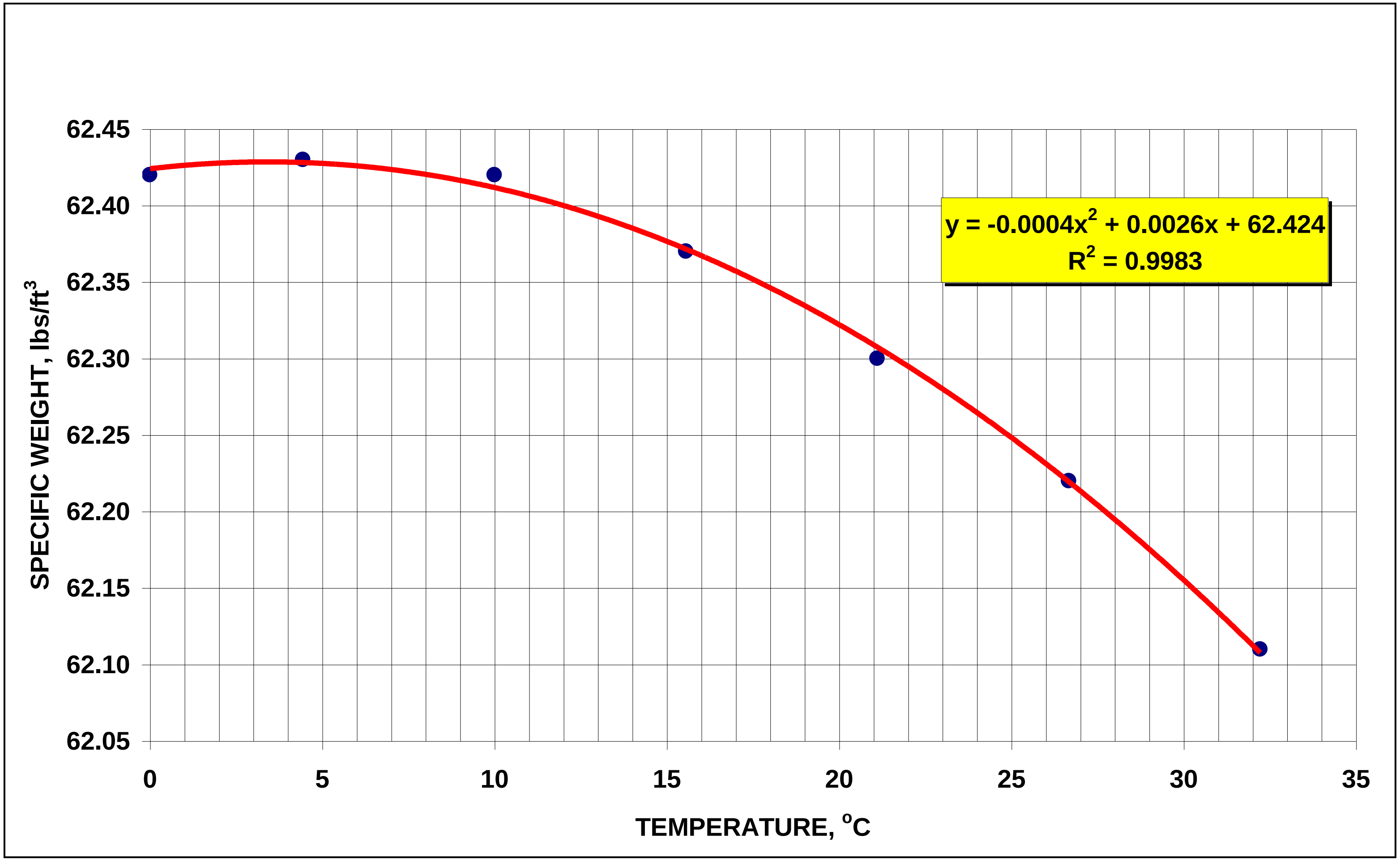
g - gravitational constant, 32.174 ft/sec^2

V - volume each stage, ft^3

μ - viscosity, lb.-sec/ft^2 (temp)

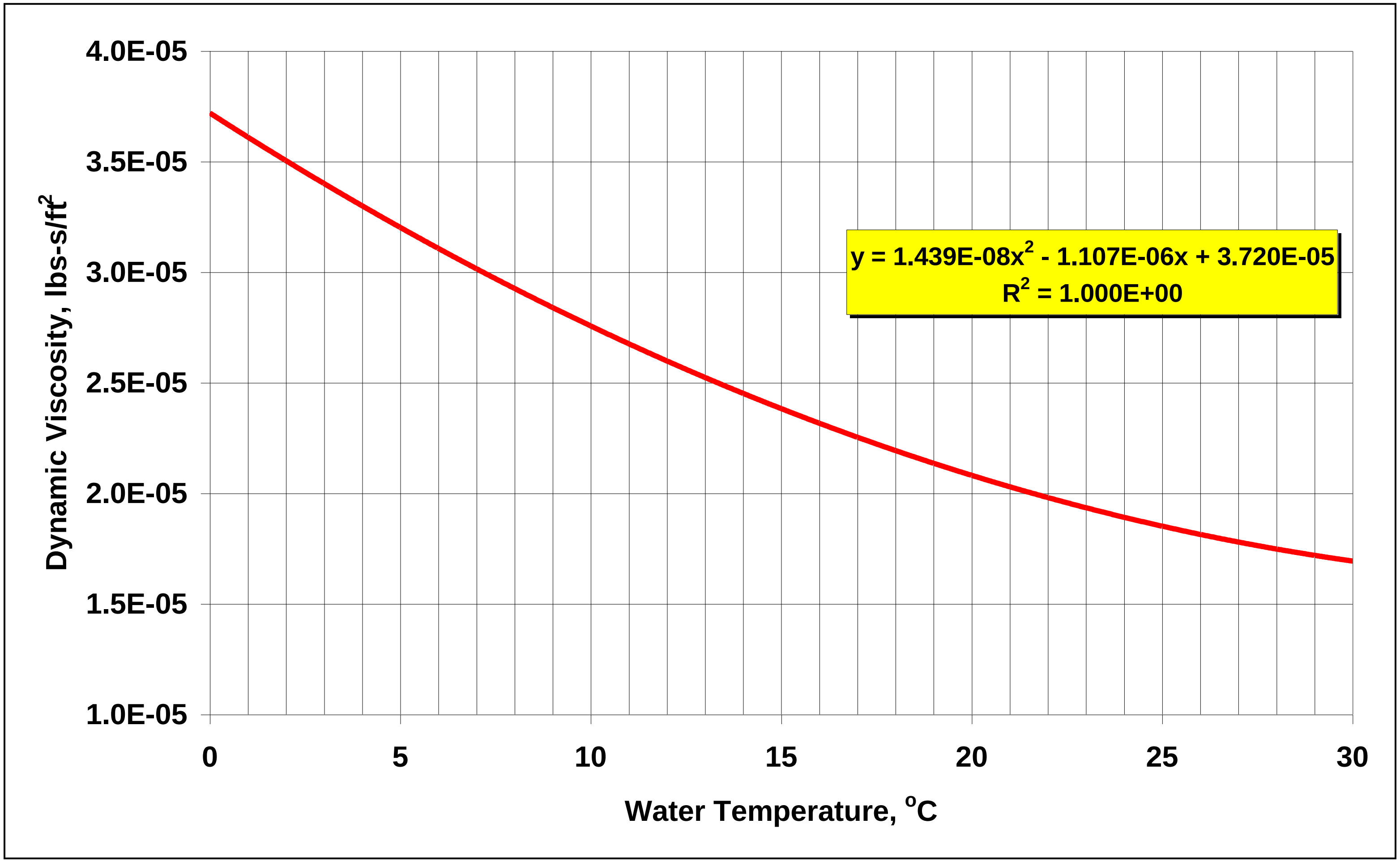
Mixing Concepts

- Water Density



Mixing Concepts

- Dynamic Viscosity



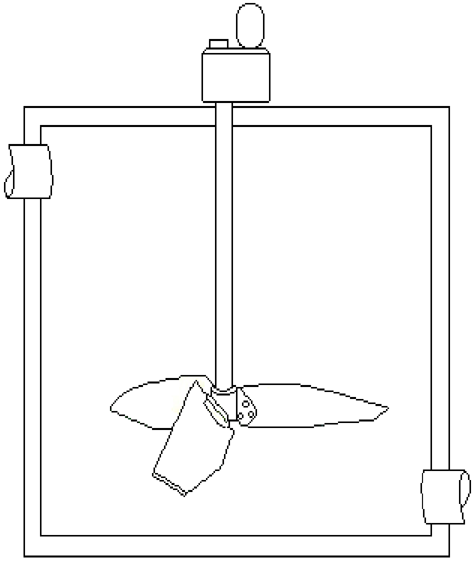
Mixing Concepts

- Basin Turnover
  - Match pumping rate and basin configuration for optimum turnover rate depending on process
  - Helps produce optimum degree of blending
  - High turnover rate wastes energy and increases mixer wear
  - Equation

$$B_t = \frac{Q_i}{V}$$

Qi = mixed flow, gpm

V = basin volume, gallons



Mixing Concepts

- Impeller Pumping Capacity
  - Defines turnover rate in rapid mixing and vertical flocculation

$$Q_i = 448.8 N_q n D^3$$

Q_i - pumping rate, gpm

N_q - impeller flow number

n - rotational speed, rps

D - impeller diameter, ft.

Mixing Concepts

- Impeller Flow Number (N_q)
  - Great enough to produce turnover
  - Avoid excess turbulence that leads to shearing
- Impeller Power Number (N_p)
  - Provide necessary mixing intensity (G value) without increasing electrical requirements
- Impeller selection important to optimize mixing capabilities
  - Matched to basin configurations and process needs
  - Avoid chemical shearing while maintaining dispersion and contact with contaminants

Mixing Concepts

- Degree of Blending
  - Depicts blending of water and chemicals within detention time provided
  - Prochazka and Landua (1961) proposed fractional unmixedness for impeller performance
  - Khang and Levenspiel (1976) proposed relationship approximate concentration fluctuations during mixing

$$a = 2e^{-kt}$$

  - Equation used to estimate degree of blending

Mixing Concepts

- Degree of Blending

$$k = \frac{N\left(d/T_e\right)^{2.3}}{0.5} \qquad a = 2e^{-kt}$$

$$B\% = (1-a)*100$$

e - base e exponential (natural logarithm)

k - decay rate

t - detention time, seconds

N - impeller speed, rps

d/Te - impeller diameter/basin diameter ratio

Mixing Concepts

- Displacement Factor (*D*/*F*)
  - E.L. Bean proposed displacement factors for paddle mixers
    - Estimate pumping capacity of paddles (*D*)
    - Dividing by flow rate gives displacement factor (*D*/*F*)
    - >30 for effective mixing and floc development
  - Sum of *D* for each assembly can be used to estimate turnover each stage

Mixing Concepts

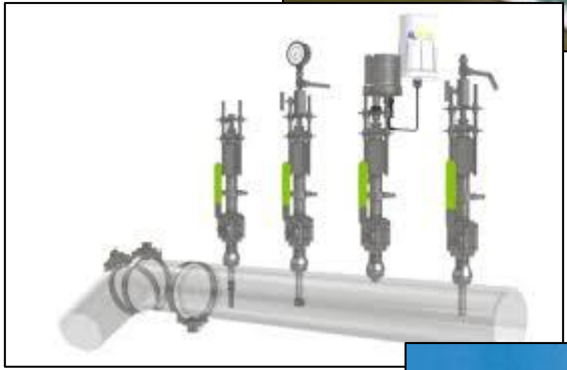
- Displacement Factor (D/F)

$$d = 2a\pi r(rpm) \qquad D = \sum d \qquad \frac{D}{F} \geq 30$$

D - sum of individual d for paddles, ft^3/min
F - basin flow rate, ft^3/min
d - displacement each paddle, ft^3/min
a - area of each paddle, ft^2
π - 3.1416
r - radius from outer edge each paddle, ft
rpm - rotational speed, rpm

Optimal Mixing Characteristics

- Optimal Mixing Characteristics
  - Dependent on process used
  - Important features include
    - Detention time
    - Chemical injection point
    - Mixing intensity (G value)
    - Basin turnover
    - Counter-current flow
    - Degree of blending
    - Gt values
    - Displacement factor (flocculation)
    - Impeller selection and pumping capacity



Optimal Mixing Characteristics - Pipe Mixing

Detention time, sec.	1 to 3
Turnover rate, per sec.	0.6 to 3.5
Pipe length/diameter ratio	≥10
G value, sec^{-1}	≥500
Gt value	500 to 2,500

Optimal Mixing Characteristics - Static Mixing

Detention time, sec.	<1
Pipe length/diameter ratio	≥ 10, ≥ 5
G value, sec^{-1}	≥ 500
Gt value	200 to 500

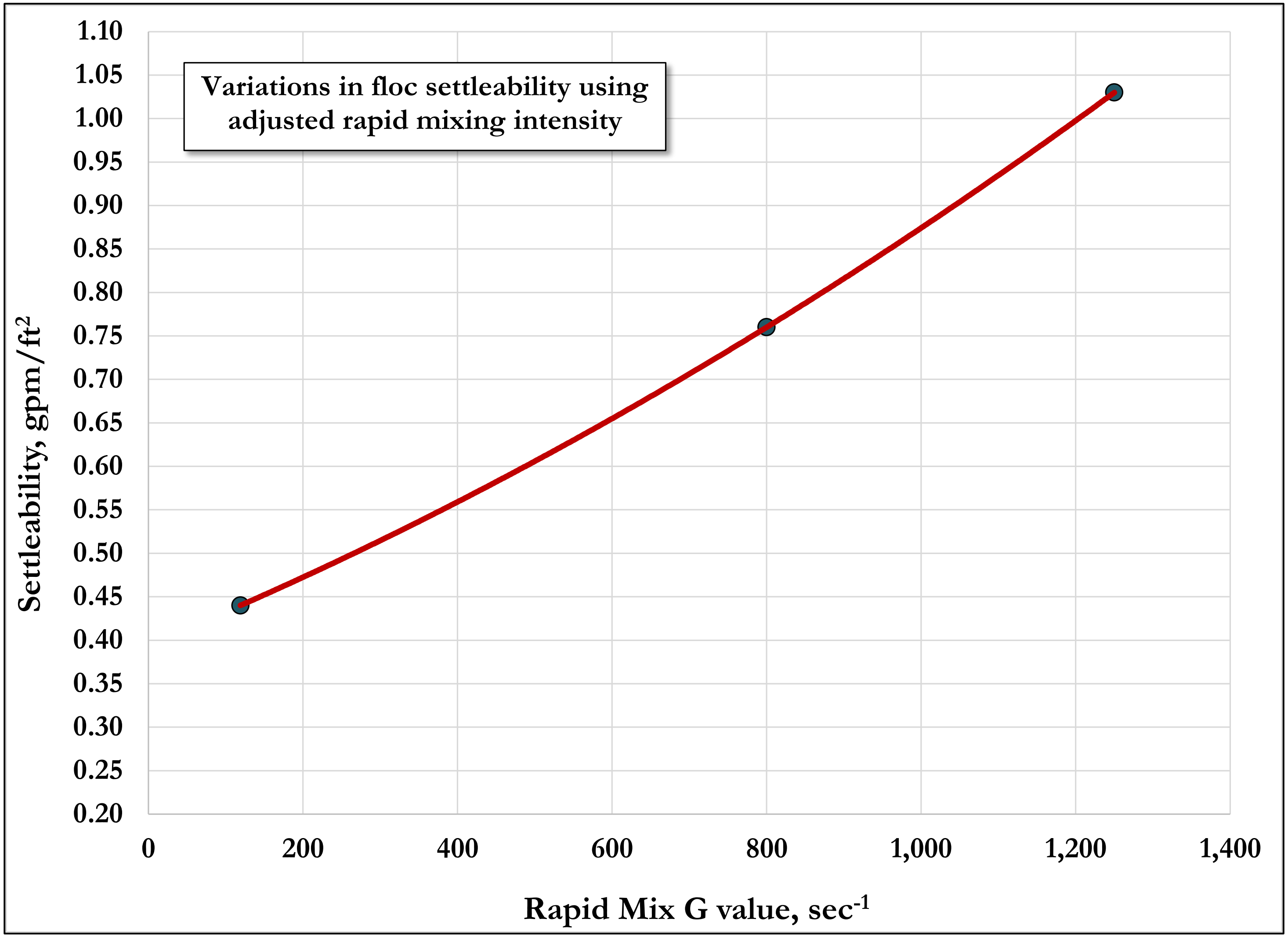
Optimal Mixing Characteristics - Inline Mixing

Detention time, sec.	±1
Turnover rate, per min.	≥1.5
Impeller/pipe diameter ratio	0.3 to 0.6
Length/diameter ratio	2 to 2.5
G value, sec^{-1}	≥2,400
Gt value	500 to 2,400

Optimal Mixing Characteristics -Rapid Mixing

Detention time, sec.	10 to 15	Degree of blending, %	>99.5
Turnover rate, per min.	≥8, <13	G value, sec^{-1}	750 to 1,400
Imp/basin diameter ratio	0.3 to 0.6	Gt value	5,000 to 20,000

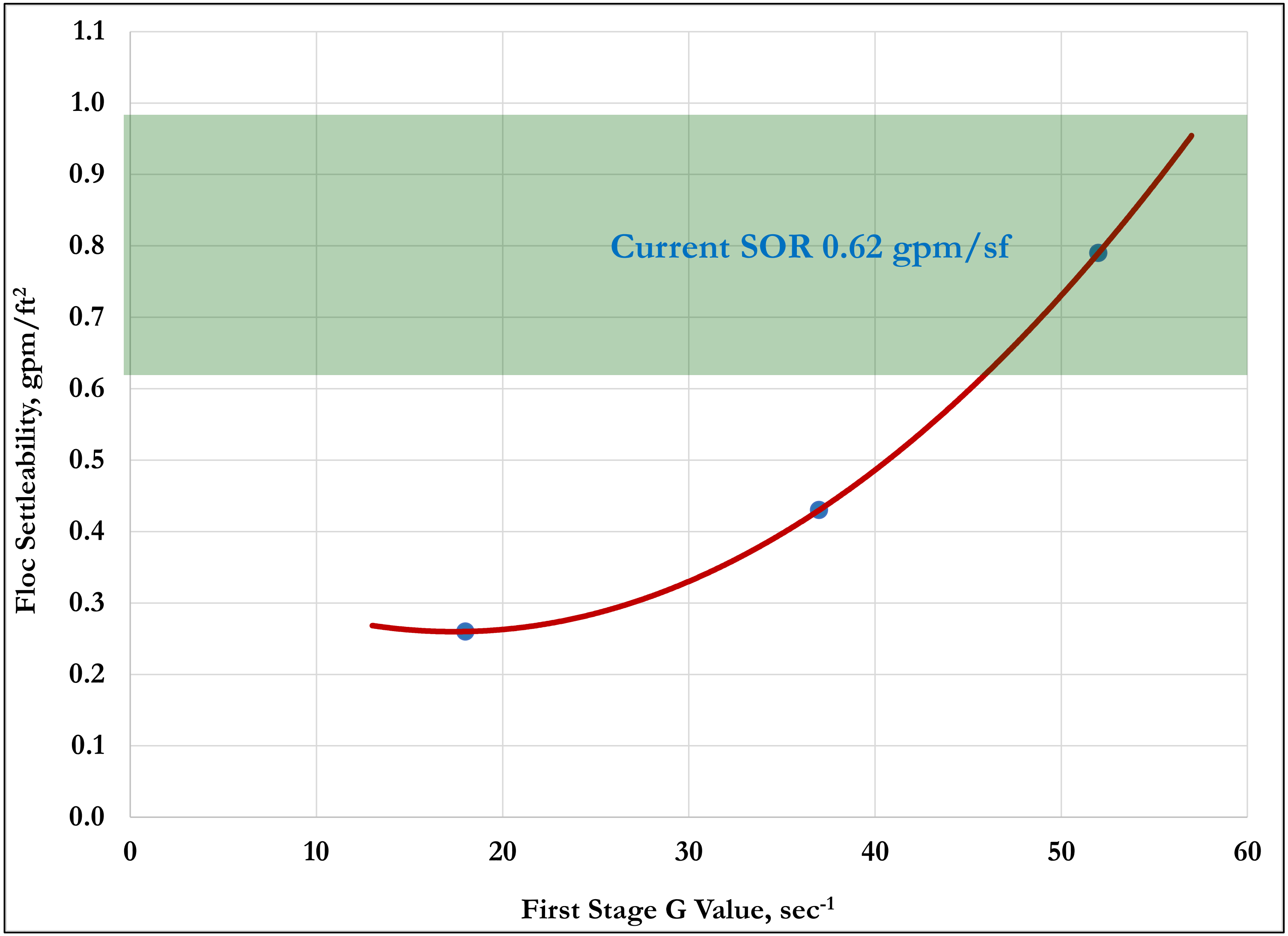
Optimal Mixing Characteristics -Rapid Mixing



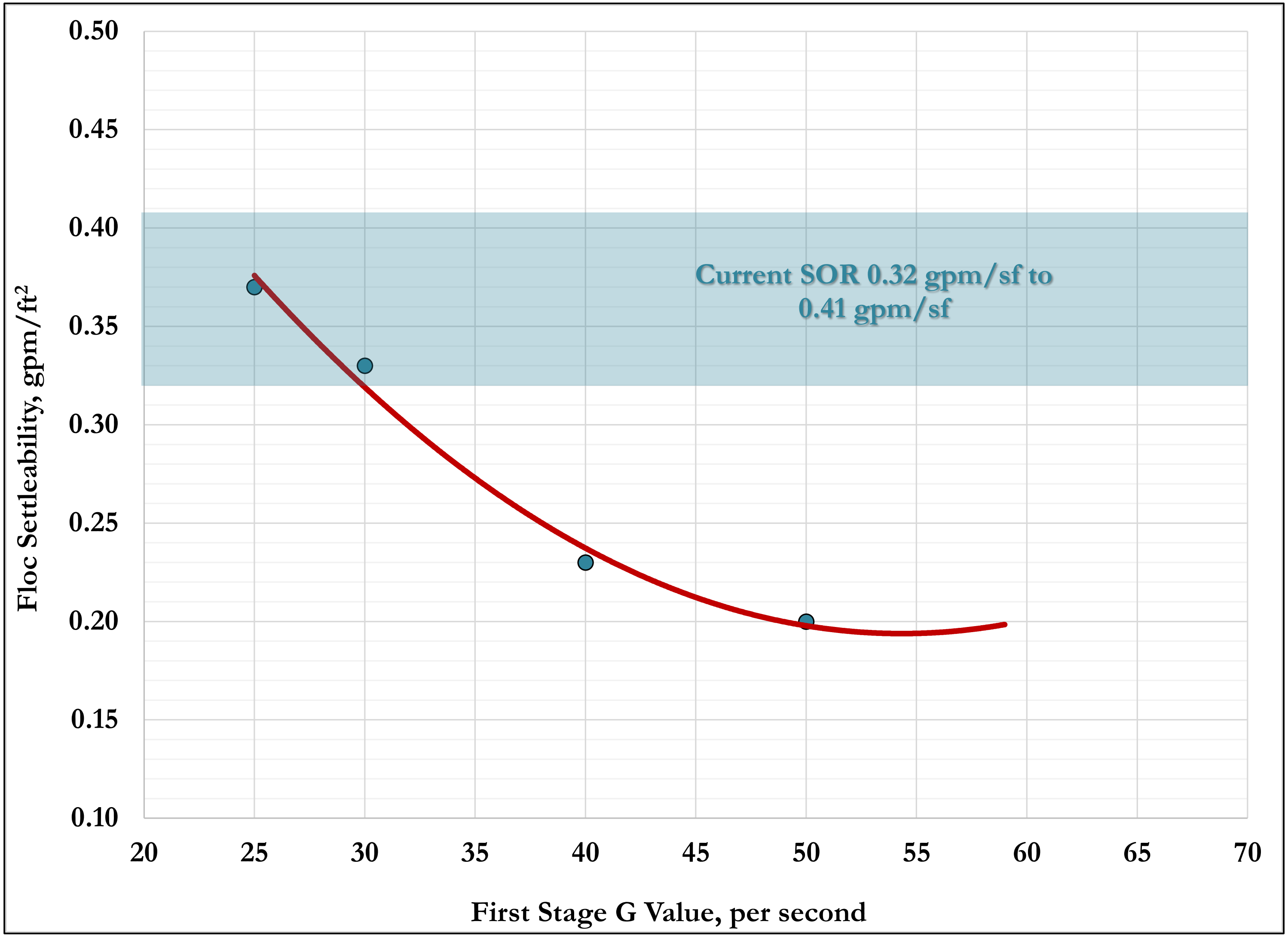
Optimal Mixing Characteristics - Flocculation Mixing

Detention time, min.	≥30	Channel velocity, fps	1.0 to 2.0
Flow thru velocity, fpm	0.5 to 1.5	d/T_e ratio horiz.	0.3 to 0.85
Stages	2 to 6	d/T_e ratio vert.	0.35 to 0.7
Area between stages, %	8 to 10	Displacement factor (D/F)	>30
Paddle area, %	10 to 25	Turnover, per min.	0.4 to 2.0
Paddle speed, fps	0.5 to 3.0	G value, sec^{-1}	10 to 80
Mixer speed, fps	2 to 8	Tapered G values, per stage	10 to 15
Outlet velocity, fps	0.75 minimum	Gt value	30,000 to 200,000

Optimal Mixing Characteristics - Flocculation Mixing

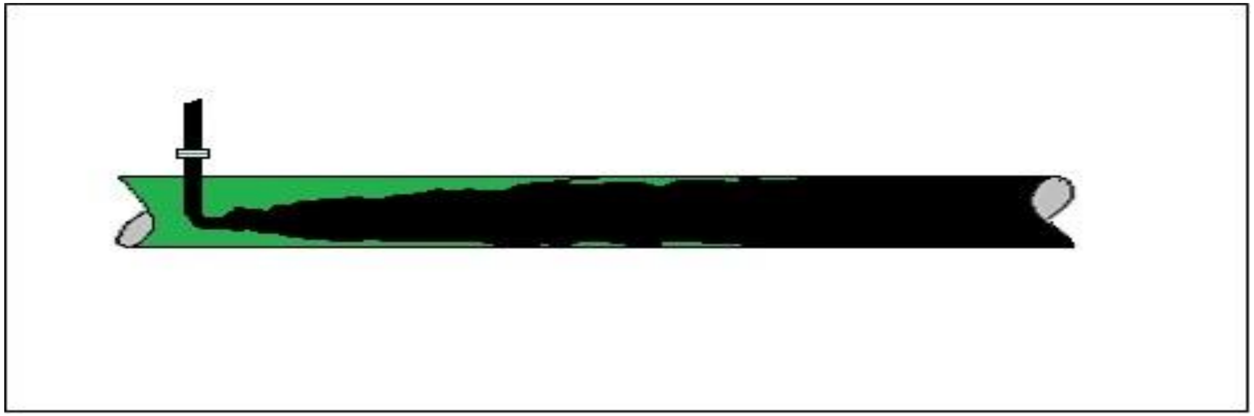


Optimal Mixing Characteristics - Flocculation Mixing



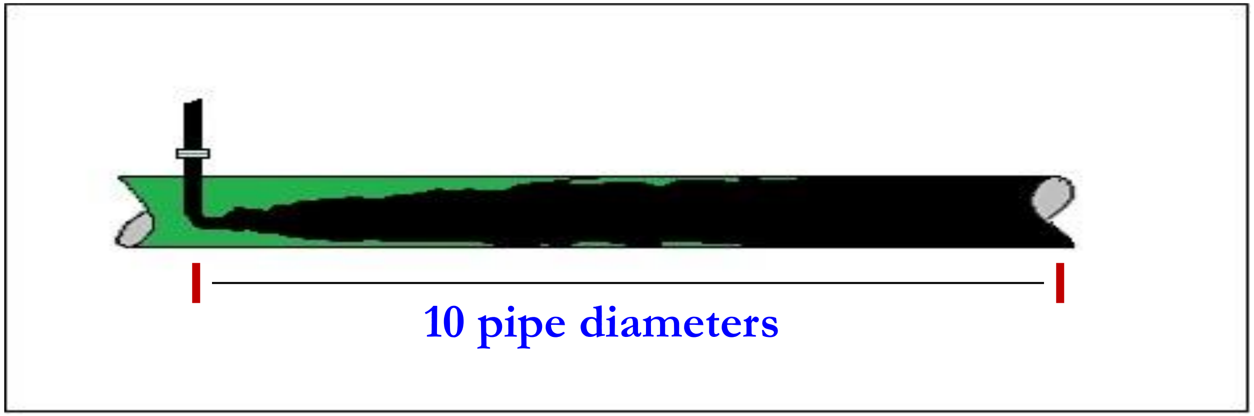
Mixing Designs

- Pipe Mixing
  - Chemical dispersion using pipe turbulence and retention
  - Turbulence should be verified using Reynolds number (>4,000)
  - Generally, G values ≈500 sec^{-1} needed to disperse applied chemical
    - Most researchers agree on 500 G for adequate chemical dispersion
    - Promotes more thorough mixing and contact between water and reactants



Mixing Designs

- Pipe Mixing
  - Chemical applied at least 10 pipe diameters upstream of reacted water zone

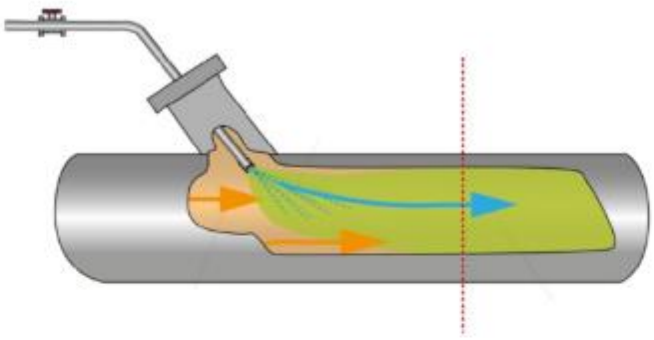


  - G values then function of head losses in pipe system
  - 500 sec^{-1} creates adequate mixing for dispersion
  - >300 sec^{-1} shears polymers (caution)

Mixing Designs

- Pipe Mixing
  - Equation

$$G, sec^{-1} = \left(\frac{QwH}{V\mu}\right)$$



G = G value

Q = pipe flow rate, cubic feet per second

w = specific weight of water (temp. dependent)

H = head loss in pipe, ft.

V = volume of pipe under mixing, ft^3

μ = dynamic viscosity, lb-s/ft^2

  - 12-inch pipe flow at 6.3 ft/sec @20°C will exhibit G of 466 sec^{-1}

Mixing Designs

- Static Mixers
  - Pipeline mixers with no moving parts
    - Sizes up to 60-inch diameter
  - Mixing veins produce turbulence within mixer body
    - Turbulence proportional to flow and head loss (from manufacturer)
  - Particularly effective for chlorine feed and phosphate feed chemicals

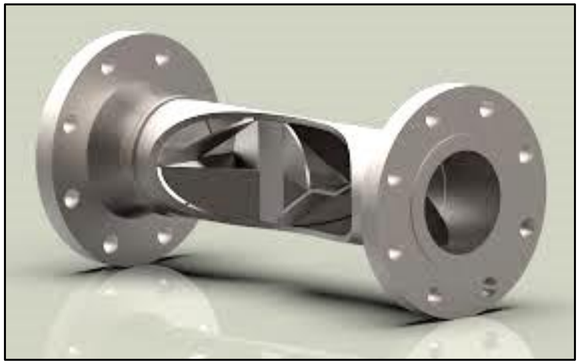
Mixing Designs

- Static Mixers
  - Need 10 pipe diameters upstream and 5 pipe diameters downstream
    - Aids in flow stabilization at inlet and outlet
  - Good for chemical dispersion
  - Detention times typically one second or less
  - Should be sized so that customary flow is near maximum for mixer body

Mixing Designs

- Static Mixers
  - Equation

$$G, sec^{-1} = \left(\frac{QwH}{V\mu}\right)$$



G = G value

Q = mixer flow rate, cubic feet per second

w = specific weight of water (temp. dependent)

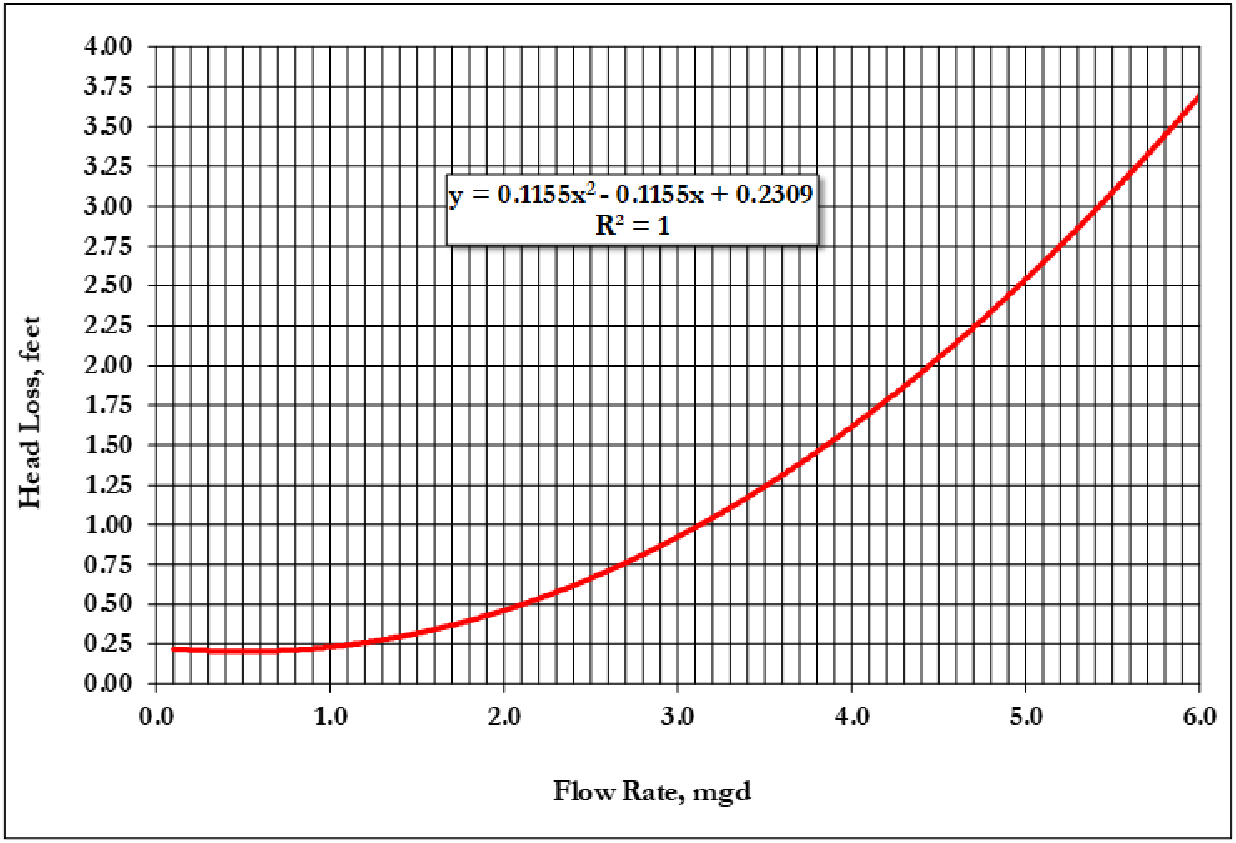
H = head loss in mixer body, ft.

V = volume of mixer body, ft^3

μ = dynamic viscosity, lb-s/ft^2

Mixing Designs

- Static Mixers
  - Head loss proportional to flow (manufacturer's data)



Mixing Designs

- Weir Mixing
  - Head loss over weir creates turbulence
  - Chemical application at the point of greatest turbulence
  - Turbulence induces mixing intensity (G value)
  - Good for chemical dispersion
    - Very efficient for polymer treatments at low head loss or longer retention times

Mixing Designs

- Weir Mixing
  - Equation

$$G, sec^{-1} = \left(62.5\frac{H}{t\mu}\right)^{0.5}$$

G = G value

H = head loss over weir, ft.

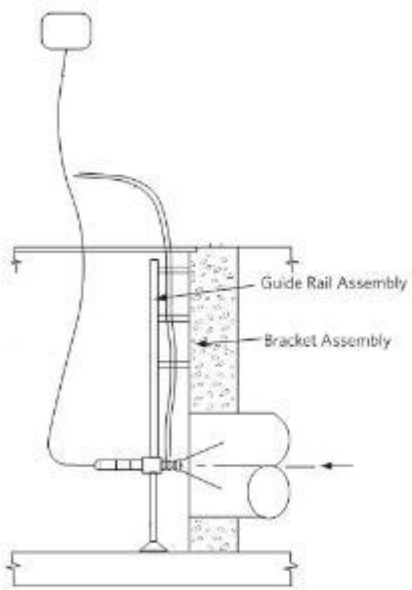
t = mixing retention time, sec

μ = dynamic viscosity, lb-s/ft^2

  - Rectangular weir with retention time zone of 8 seconds and 2-inches head loss @20^{o}C creates G of 250 sec^{-1}

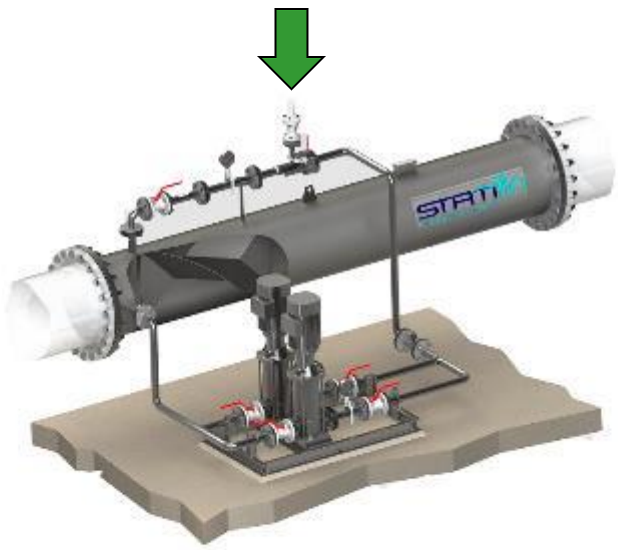
Mixing Designs

- Pump Mixers
  - Chemical feed pumped directly into pipe flow path
  - Chemical injection in pump impeller or through orifice
    - Water Champ is an example
    - Other systems exist
  - Rapid chemical dispersion actively increases contact with water
    - Conical discharge plume fills pipe area
    - Prone to scale build up at spray nozzles



Mixing Designs

- Pump Mixers
  - Chemical feed pumped directly into pipe flow path
  - Chemical injection in pump impeller or through orifice
  - Designed chemical pumping system can be used to improve mixing efficiency
    - Pump draws suction from pipe system and re-injects chemical solution back into pipe through a jet or orifice
    - Chemical injected into pump discharge pipe prior to re-entry into main pipeline

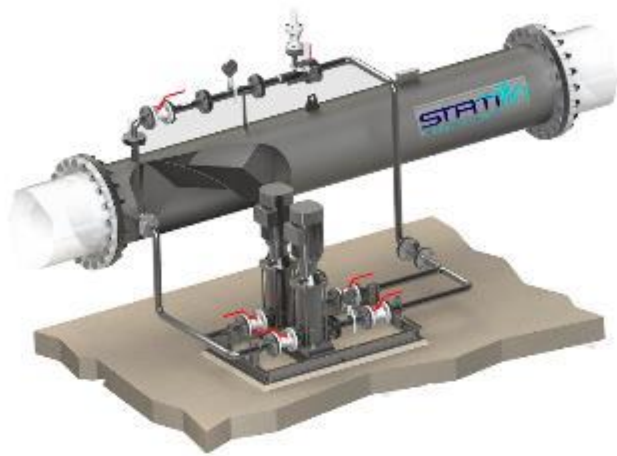


Mixing Designs

- Pump Mixers
  - G value equation can vary

$$P = QH\rho g\eta$$

    - P = power input,
    - Q = pump flow rate. ft3/sec
    - H = pump head, ft
    - ρ = water density, lbs/ft3
    - g = gravitational constant 32.174 lbs/ft
    - η = pump efficiency, %
  - Then insert into G value equation



Mixing Designs

- Rapid mixing concepts for chemical dispersion
- Flocculation concepts for effective floc development
- G value relationship to process control

Mixing Designs

- Rapid Mixing
  - Importance well documented
  - Turbulence to disperse chemicals and water to initiate coagulation
  - Matched to coagulation mechanism used
    - Adsorption and charge neutralization
    - Enmeshment in a precipitate (sweep coagulation)
    - Adsorption and interparticle bridging
    - Mixing disinfection chemicals reduces unwanted byrpoducts

Mixing Designs

- In-line Rapid Mixing
  - Instantaneous high energy mixing for charge neutralization
  - Destabilization of particles requires collision and transport of particles and formed hydrolyzed coagulant species
  - Chemical dissociation to metal cations (M^{+n}) and salt anions (S^{-n})

Mixing Designs

- Chemical dispersion
  - Dissociation reactions

$$Al_2(SO_4)_3 \Rightarrow 2Al^{+3} + 3SO_4^{-2}$$

$$FeCl_3 \Rightarrow Fe^{+3} + 3Cl^{-}$$

$$Fe_2(SO_4)_3 \Rightarrow 2Fe^{+3} + 3SO_4^{-2}$$

  - Generalized chemical species - $M_x(OH)_y^{+n}$
    - Dissociation reactions takes less than one second

Mixing Designs

- Chemical dispersion
  - Common chemical reactions

$$Al_2(SO_4)_3 + 3Ca(HCO_3)_2 \Rightarrow 2Al(OH)_3 + 3CaSO_4 + 6CO_2$$

$$2FeCl_3 + 3Ca(HCO_3)_2 \Rightarrow 2Fe(OH)_3 + 3CaCl_2 + 6CO_2$$

$$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \Rightarrow 2Fe(OH)_3 + 3CaSO_4 + 6CO_2$$

  - Reaction times for metal hydroxide development - seven (7) seconds

Mixing Designs

- Conventional Rapid Mixing
  - Detention times for chemical mixing are longer
    - Create metal hydroxides that do the treatment
    - Precipitation of phosphates and adsorption of organics and turbidity particles
  - Use conventional mixing basin
  - Most treatment occurs in flocculation as collisions occur between floc and particles in water
    - Lower mixing intensity used in floc development

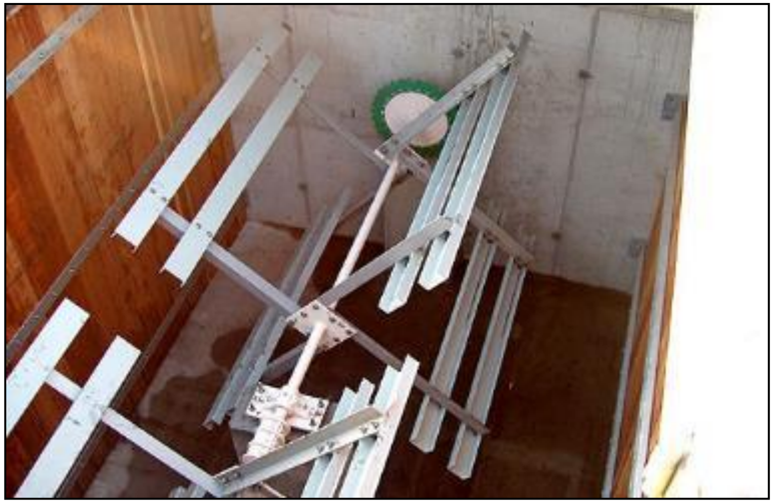
Mixing Designs

- Adsorption and Interparticle Bridging
  - Simultaneous treatment with polymers
  - Polymer strand length depends on MW
  - Charged sites along polymer strand
    - Foster adsorption of opposite charged particles
    - Multiple strands or looping on single strand creates bridging effect
    - Increase size, density, settleability of floc formed

  - Polymers generally shear at G values greater than 300 sec^{-1}
    - Make take 45 minutes to 2 hours to reform polymer strand after shearing

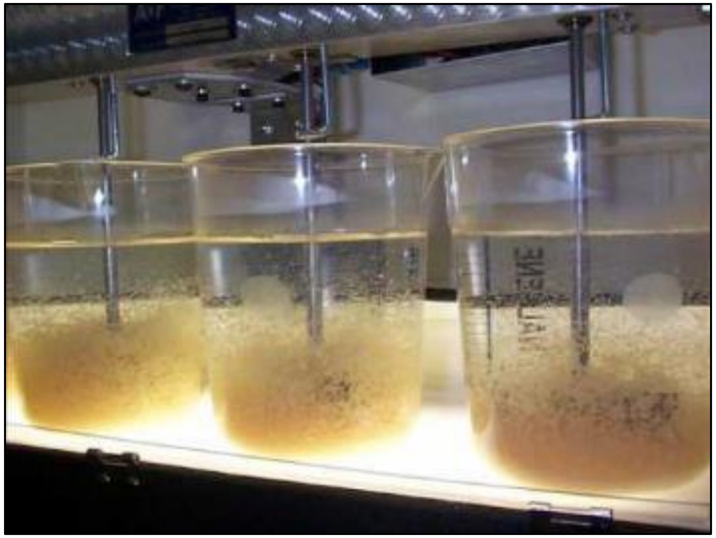
Mixing Designs

- Flocculation
  - Gentle mixing to transform initial floc formations into dense settleability material
  - Treatment governed by number of particles in suspension, collisions between particles to increase size and density
  - Operational control over chemical dosage and mixing intensity (energy) applied - *particle collisions*
  - Tertiary treatment in wastewater for phosphorus removals using chemical precipitation (pH important



Mixing Designs

- Flocculation
  - Orthokinetic flocculation most common method
    - Involves bulk fluid motion using mixing intensity to gather chemical and particles into floc
  - Horizontal or vertical flocculation assemblies used
  - Mixing energy successively lowered as process proceeds
    - Tapered mixing promotes dense floc formation for effective settling
    - G values and tapering sequences optimized using jar tests

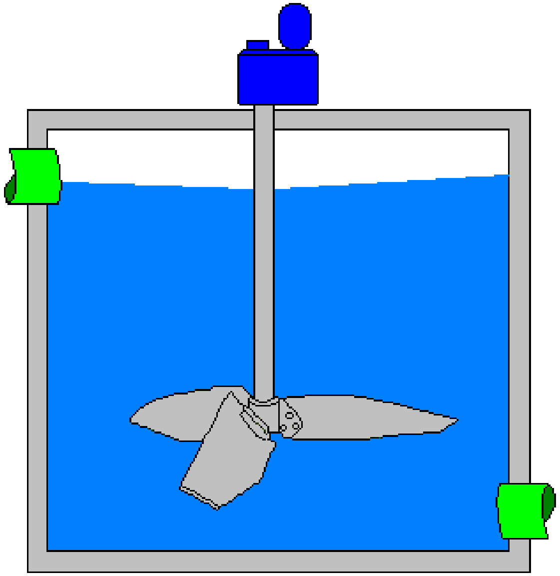


Mixing Designs

- Flocculation
  - Two or more chambers or stages
  - Floc develops increasing size to maximum diameter
    - Floc formation 12 minutes to 17 minutes
  - Further mixing promotes compaction of floc reducing size and increasing density
    - Total detention 17 minutes to 25 minutes optimizes floc development
  - Long detention times (>45 minutes) increase potential for floc shear and poor settling

Mixing Designs

- Flocculation
  - TSS recommends 30 minutes at design flow for flocculation
    - Can lead to more than 45 minutes at operating flows
  - Typical floc diameter range 0.5 mm to 3 mm
  - Match mixing and floc development to optimize density and settleability
    - Conduct floc settleability at different mixing conditions



Mixing Designs - Impellers

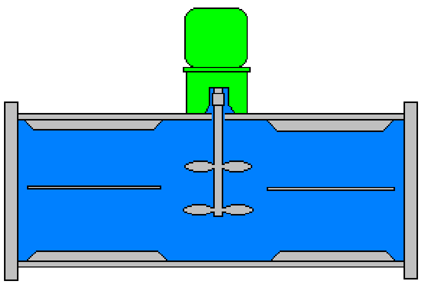
- Conventional Mixing
  - Impeller selection important to basin configuration and design
  - Radial flow impellers 90° outward from shaft
    - Produces pumping action with basin walls
    - Flow both upward and downward returning to impeller shaft
    - Reduces short-circuiting
    - Bulk rotation can be corrected with baffles

Mixing Designs - Impellers

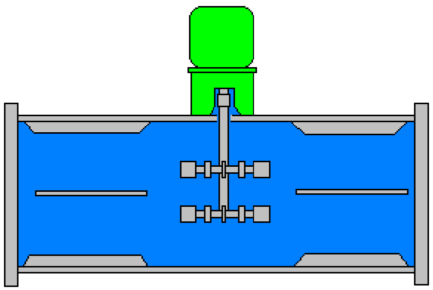
- Conventional
  - Axial flow impellers angled flow from shaft
    - 45^{o} common, but other angles used
    - Produces upward or downward pumping action depending on rotating direction
    - Must specify pumping direction
    - Pumping action opposite inlet flow to reduce short-circuiting (countercurrent flow)

Mixing Designs - Impellers

- Inline Mixers



Axial Flow



Radial Flow

Mixing Designs - Impellers

- Inline Mixers

Mixing Designs - Impellers

- Designed for mixing applications
  - Blending, turbulent mixing, viscous solutions, mixing gases and liquids
- Operations verified under lab conditions
  - N_p - *power number*
  - N_q - *flow number*
  - Mixing conditions (velocity profiles)

Mixing Designs - Impellers

Impeller	Manufacturers	Power number	Flow number
	Radial turbine 4 blade Most manufacturers	4.3	0.68
	Radial turbine 5 blade Most manufacturers	5.4	0.73
	Radial turbine 6 blade Most manufacturers	6.0	0.72
	Radial turbine 8 blade Most manufacturers	7.8	0.82

Mixing Designs - Impellers

Impeller	Manufacturers	Power number	Flow number
	Radial turbine 12 blade Some manufacturers	9.9	0.89
	Propeller Lightnin' A100/110 Chemineer AP-3	0.32 (1.0 pitch) 0.62 (1.5 pitch) 1.0 (2.0 pitch) 1.35 (2.5 pitch)	No data
	Pitched blade turbine Lightnin' A200 Chemineer P-4 Philadelphia PBT	1.27	0.79
	Flat turbine Lightnin' A200 Chemineer P-4 Philadelphia PBT	3.4	0.62

Mixing Designs - Impellers

Impeller	Manufacturers	Power number	Flow number
	High % hydrofoil Lightnin' A310/510 Chemineer SC-3	0.30	0.56
	High % Chemineer HE-3 Philadelphia hydrofoil	0.20 to 0.26	0.46 to 0.49
	Pitched fluid foil Lightnin' A320/340 Philadelphia HS	0.64	0.64
	Gas mixing Lightnin' A130 Chemineer CD-6 Philadelphia Smith Turbine	3.2	0.61

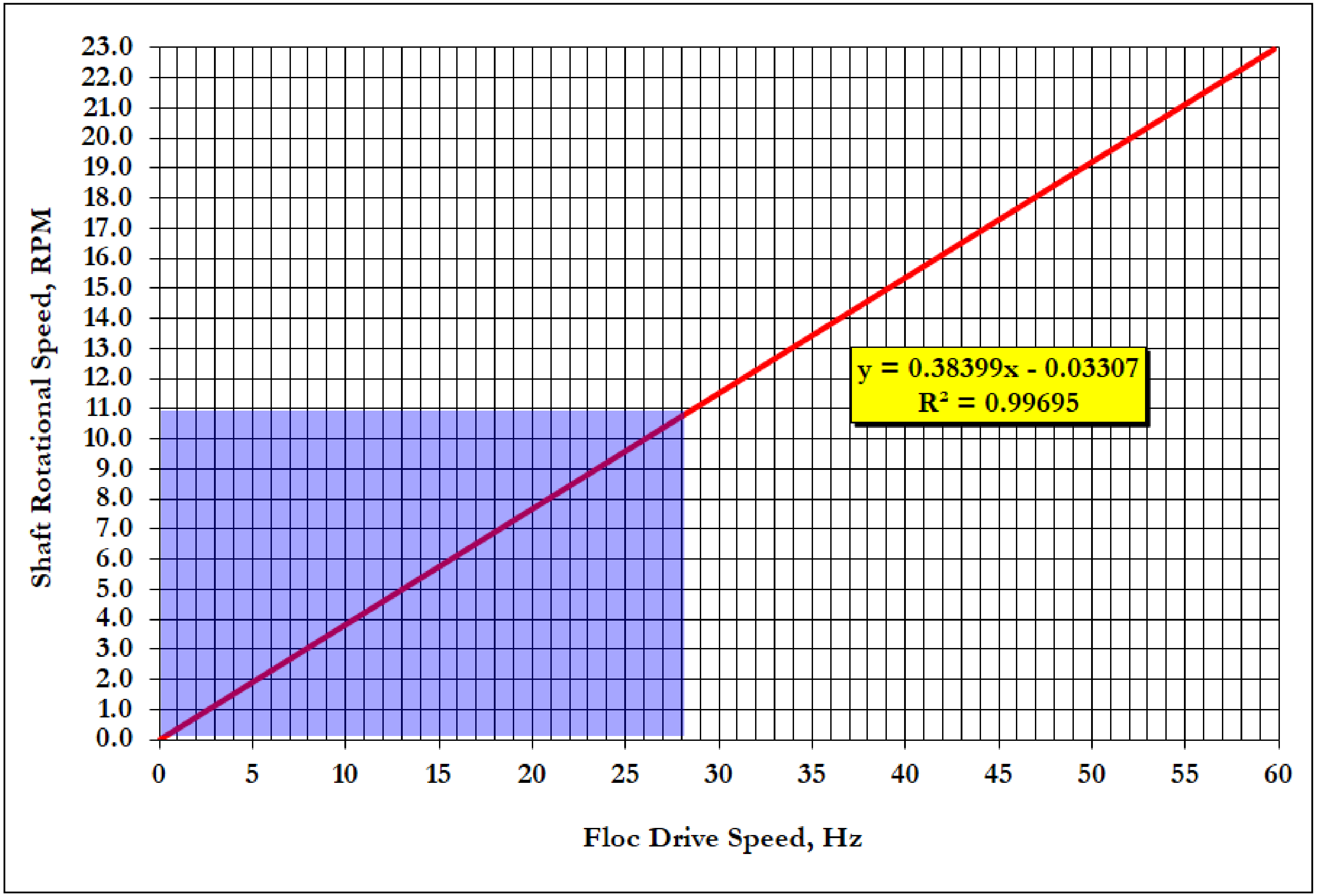
Mixing Designs - Paddles

- Different flocculator designs from manufacturers
- Most common
  - Horizontal paddle
  - Vertical mixers
  - Walking beam old technology, but still in use

Mixing Designs VFDs

- Variable frequency drives (VFDs)
  - Variable speed needed to adjust mixing based on water temperature and floc development
  - Speed curves typically linear relationship between VFD setting and paddle rotational speed
  - Shaft speed should be correlated to VFD settings
  - Speeds needed for G value calculations

Mixing Designs VFDs



Questions

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