REINHOLD ENVIRONMENTAL Ltd.

2011 NOx-Combustion Round Table & Expo Presentation

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Gas-Gas Mixing Fundamentals for SCR

NO_x - Combustion Round Table & Expo
Birmingham, 2011

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Gas-Gas Mixing Fundamentals for SCR

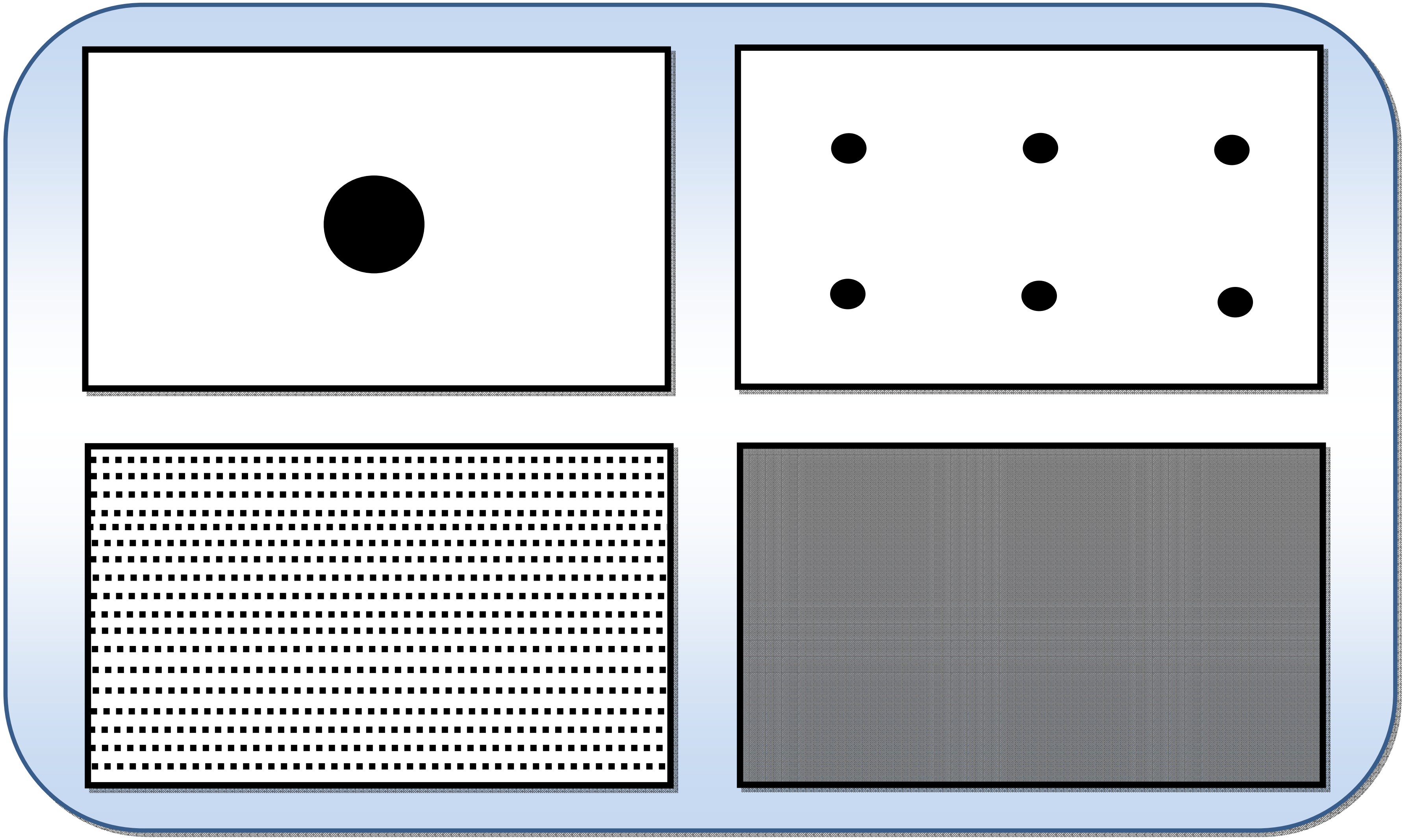
Topics

- ***Introduction***
- ***Basic Mixing Theory***
- ***Types of Mixers & Mixing Approaches***
- ***Performance Analysis for Development***
  - Effectiveness
  - Efficiency
- ***Ammonia Injection***
- ***Field Results***
- ***Summary***

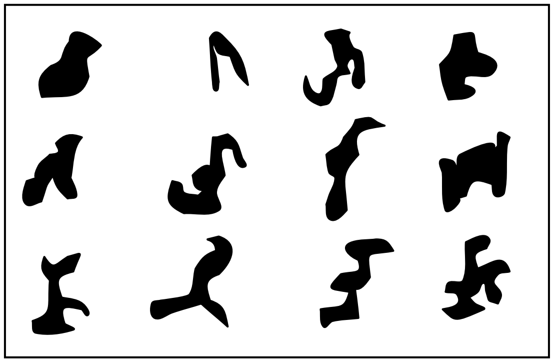
Mixing – Science & Art

- ***Art*** - Combining the science and the application in the best, most effective manner
- ***Science (Old & New)*** - Then (1940-1960) versus now (2011)
- ***Similarities across disciplines*** - Mixing of liquid-liquid, liquid-solids, liquid-gases, liquid-gases-solids, solids-solids, gases-solids, gases-gases. Many parallels in dosing, blending function, and residence time distributions
- ***Three basic degrees of freedom***
  - Process result
  - Time or distance
  - Energy

Scale of Segregation



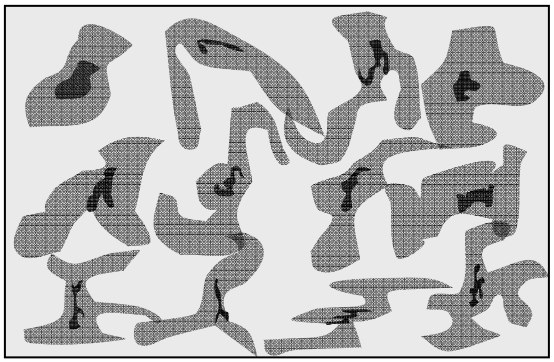
Scale and Intensity of Segregation

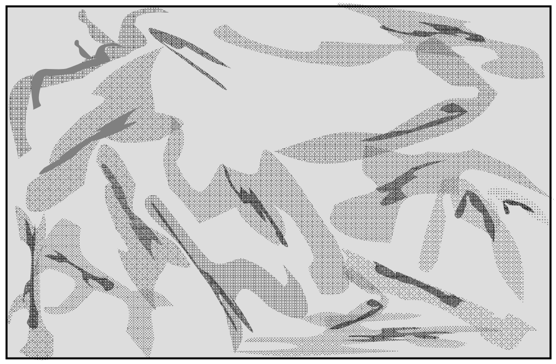


Decreasing Scale of Segregation →

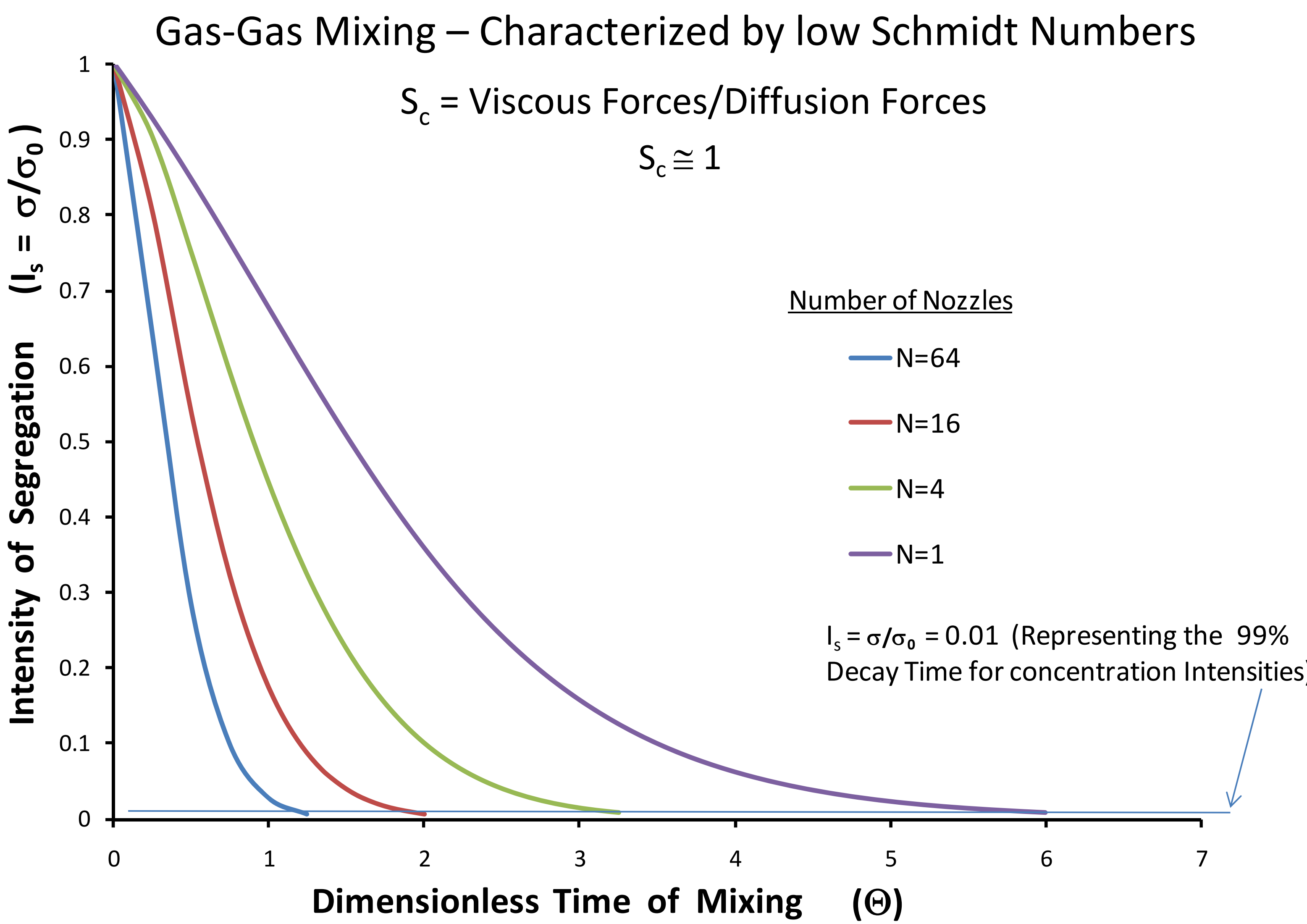
Decreasing Intensity of Segregation ↓

Decreasing Intensity of Segregation ↓

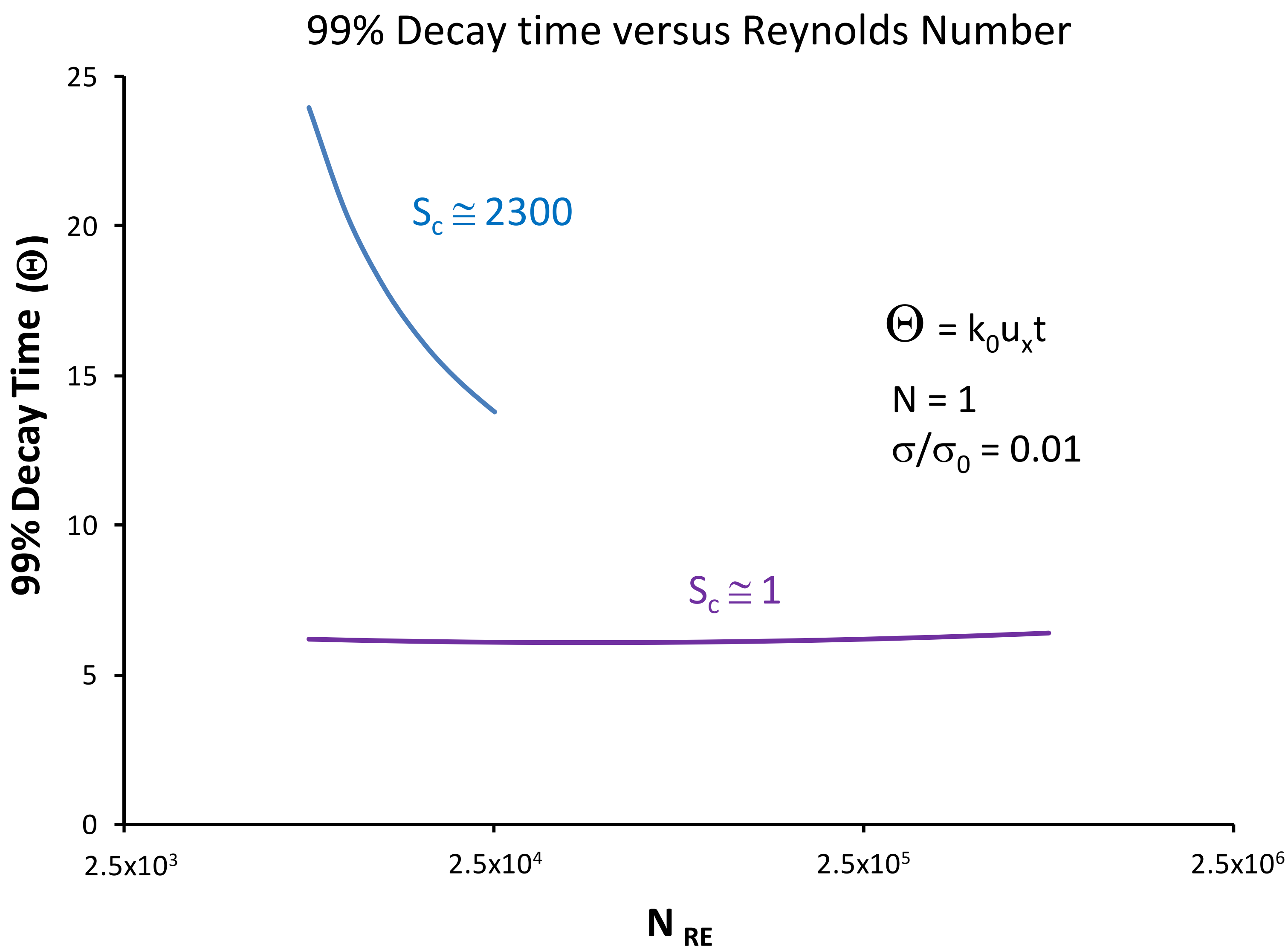




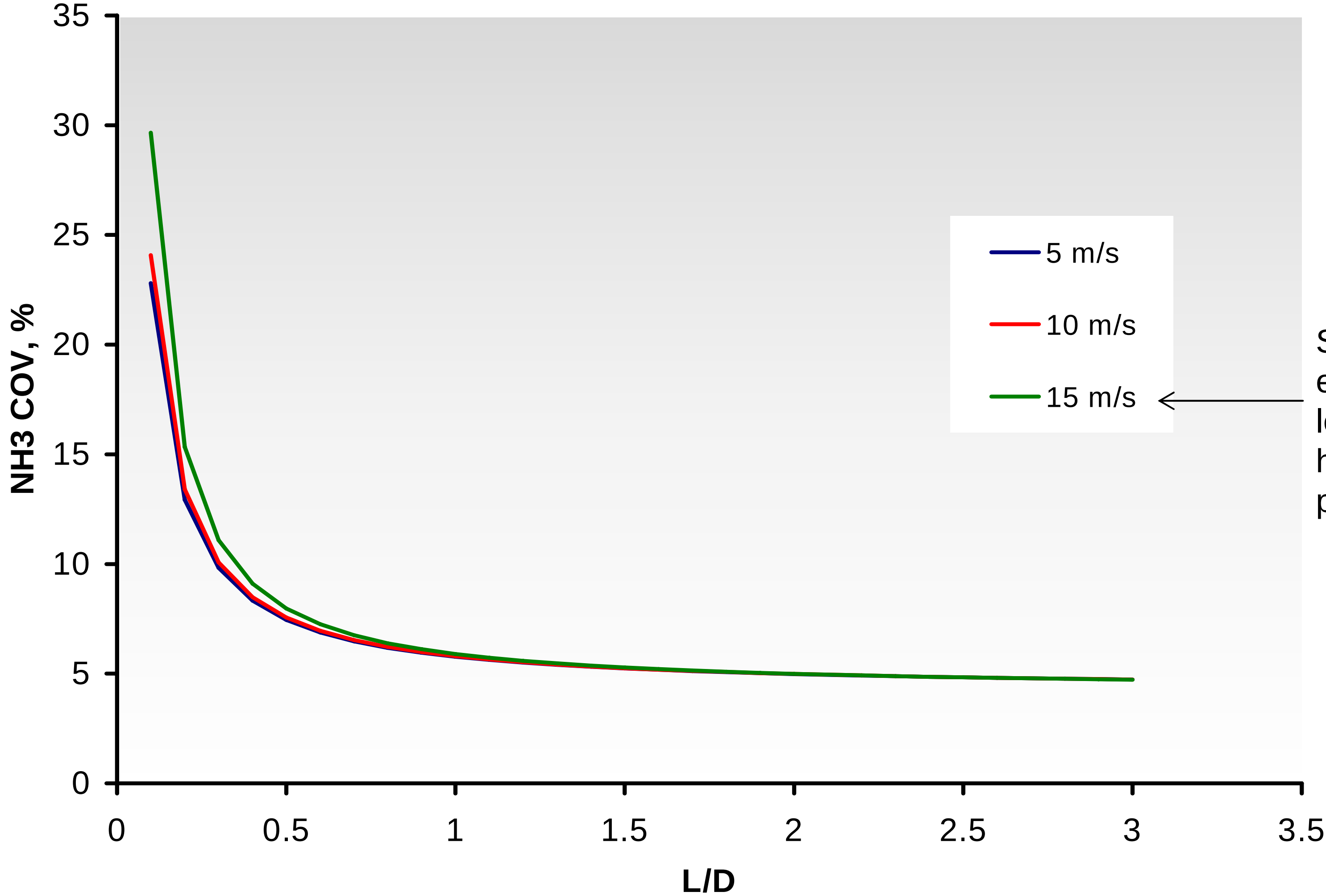
Turbulent Mixing Theory



Turbulent Mixing Theory



Effect of Velocity



Same mixing effectiveness vs length, **BUT** higher absolute pressure drop

Mixing Fundamentals

Mixing is dominated by three primary factors

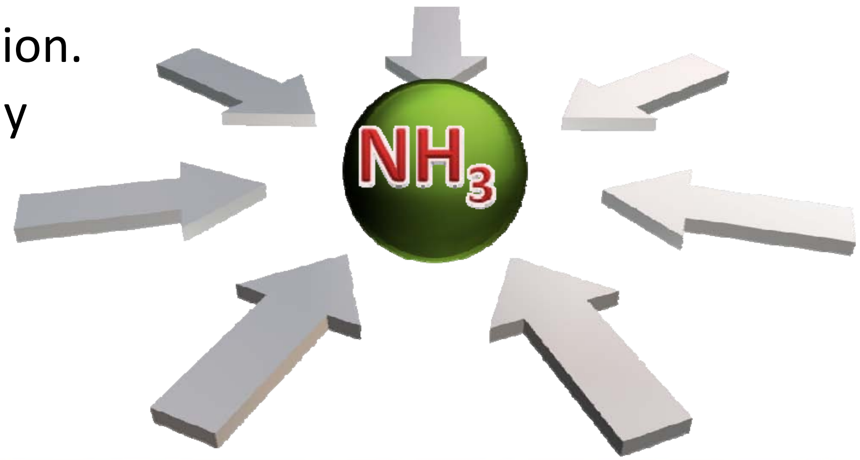
1. Original Distribution – How well a compounds are present or deposited over the space, volume or flowing stream
2. Stretching and Folding – How larger regions of varying concentrations are being divided, thinned and spread across the area via macroscopic turbulence
3. Molecular Diffusion – Occurring simultaneously throughout and necessary for the final an approach to complete homogeneity – influenced & facilitated by the increased surface area brought about by 1 & 2

SCR Ammonia Injection

Important aspects of initial ammonia dosing:

1. ***Flow Dosing*** – Matching regional or local ammonia flow to the regional or local flue gas flow (Flow profiles across the AIG are fairly stable across wide load variations – allows stable dosing of ammonia into those flow volumes)

2. ***NO_x Dosing*** – Matching of regional or local ammonia flow to the regional or local NO_x concentration (NO_x profiles more apt to change vs load or changing operation. High & low concentration regions can move, or entirely flip in position. Fixed AIG adjustments are thus inherently less stable with respect to NO_x dosing)



SCR Ammonia Injection

3. ***Spatial Dosing*** – Spacing of the injection points and thus the injection point quantity:

- One large blob, a few smaller ones, or more distributed?
- Closer spacing improves final blend of the dosed component only. There is a point of diminishing return.
- Too many increases flue blockage, pipe routing.
- Too sparse can reduce overall system effectiveness and efficiency and can over-sensitize placement relative to mixer vane, plate or disc elements.
- Optimum number and size is influenced by the design (penetrating vs non-penetrating, evaporative vs non-evaporative, deposition potential, turbulence at nozzle exit, specific mixer design, etc.)

SCR Mixer Designs

- All utility coal-fired SCR mixing applications are turbulent flow applications across the entire load range.
- Many designs have shared performance characteristics.
- With only some minor exceptions, all designs operating in utility SCR applications today;

1. Maintain a relatively constant blend across all load ranges.
2. Will experience a deterioration in the final blend entering the catalyst bed as NO_x distributions deteriorate leaving the boiler.

SCR Mixer Designs

Vortex mixers

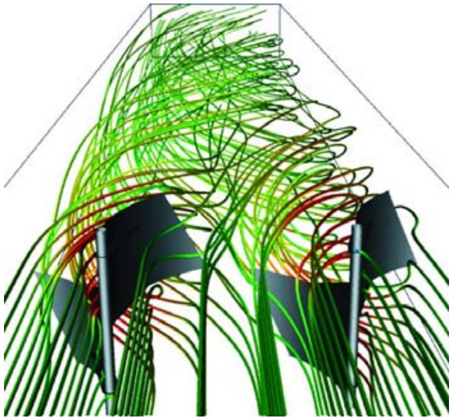
- Blend largely from downstream vortices
- A small portion of effectiveness attributable to lateral displacement of flow volumes by the upstream face of the device
- Typically lower length efficiencies. The larger the vortex, the longer the downstream distance required to fully utilize its mixing potential

Vane mixers

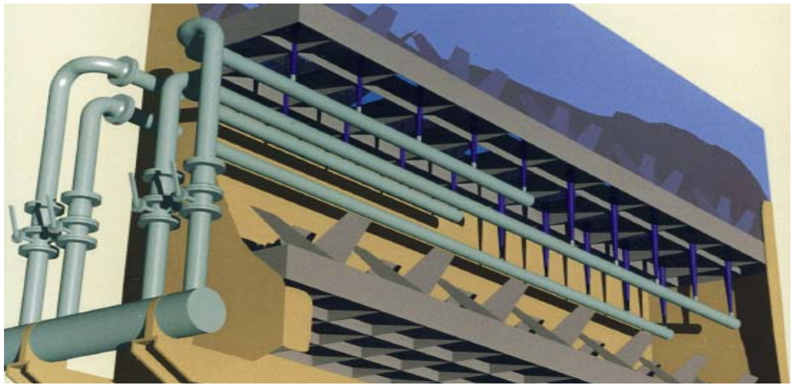
- Seek to re-direct, laterally displace, divide and recombine flow volumes
- Translocation of flow volumes is a major source of effectiveness
- In turbulent applications, vortices internal and downstream produced by exiting dissimilar flow trajectories, contribute to effectiveness
- Can have improved length efficiency over vortex. (Mixing effectiveness may also wash out in shorter distance)

<u>Hybrid mixers</u> seek to exploit the benefits of each basic concept

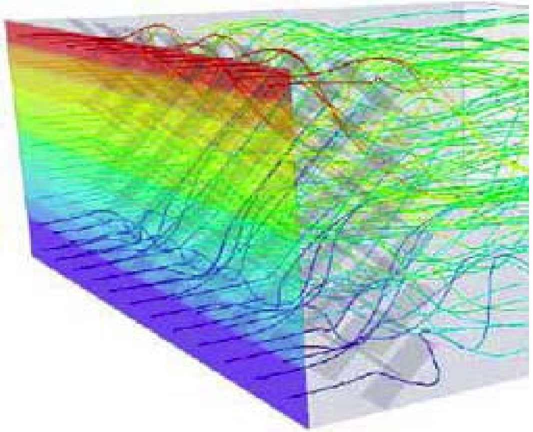
Mixer Designs and Options Vary



Sulzer Chemtech – Vane and Vortex/Hybrid

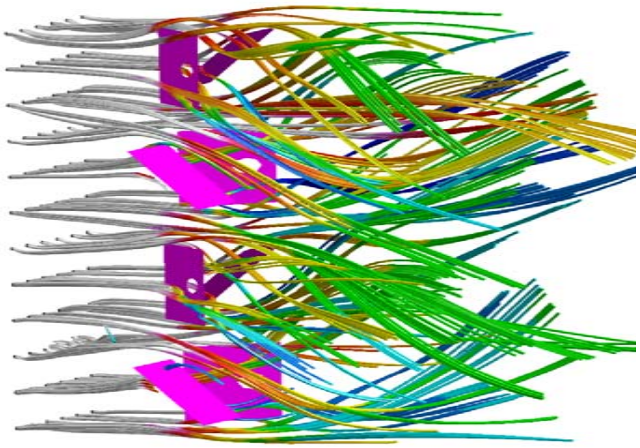


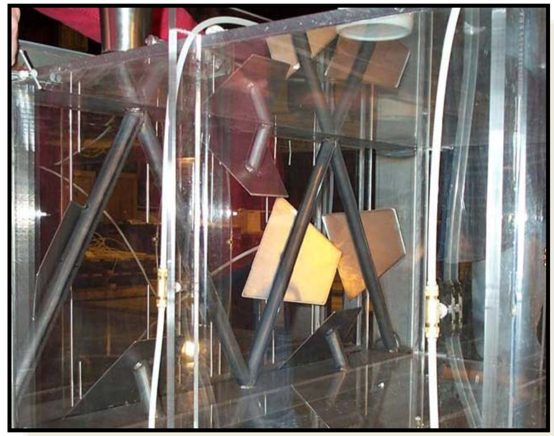
(Parmix & Turbomix – Vane/Hybrid)



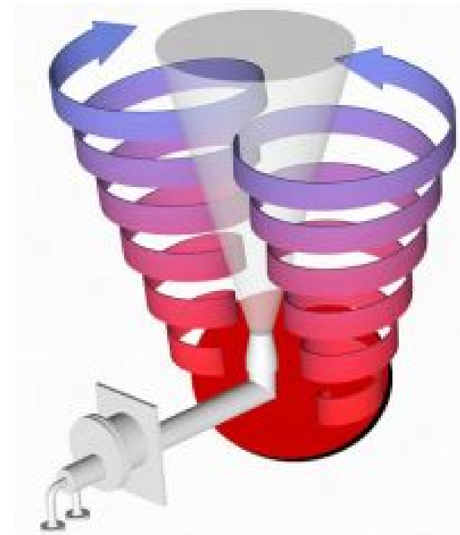
Fuel Tech – Vane/Hybrid

Mixer Designs and Options Vary

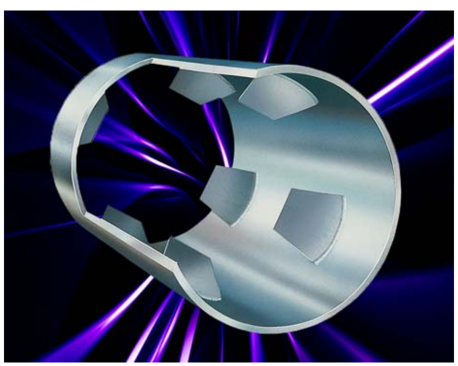




Babcock & Wilcox – Vane/Hybrid & Vortex/Hybrid



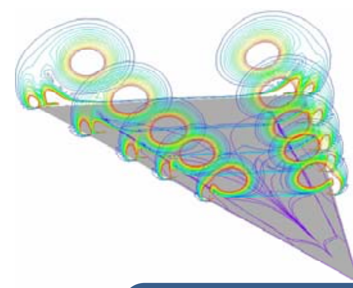
SPX Balcke-Durr (Delta Wing) Vortex



Vortex

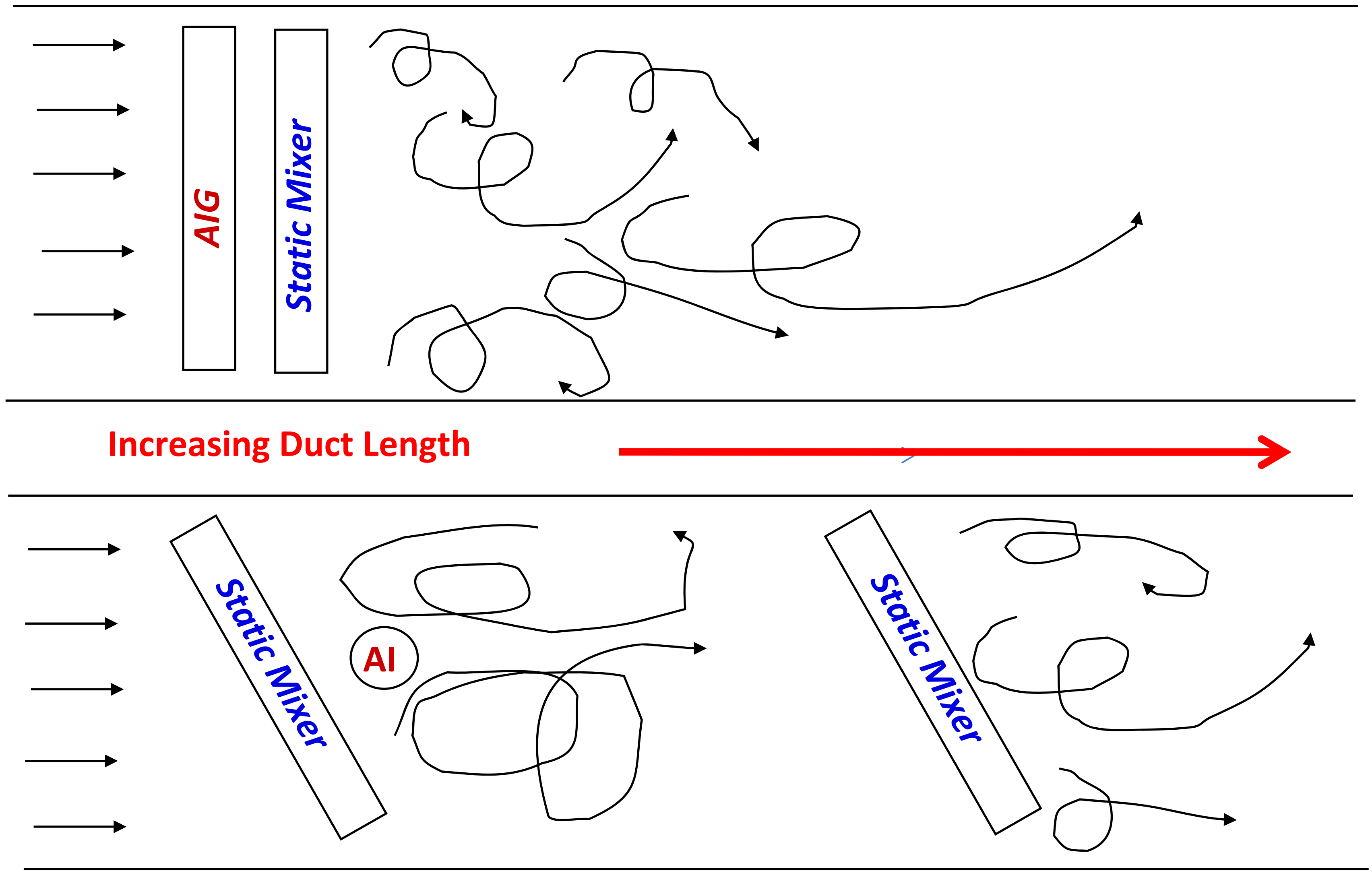
Vane/Hybrid

Others



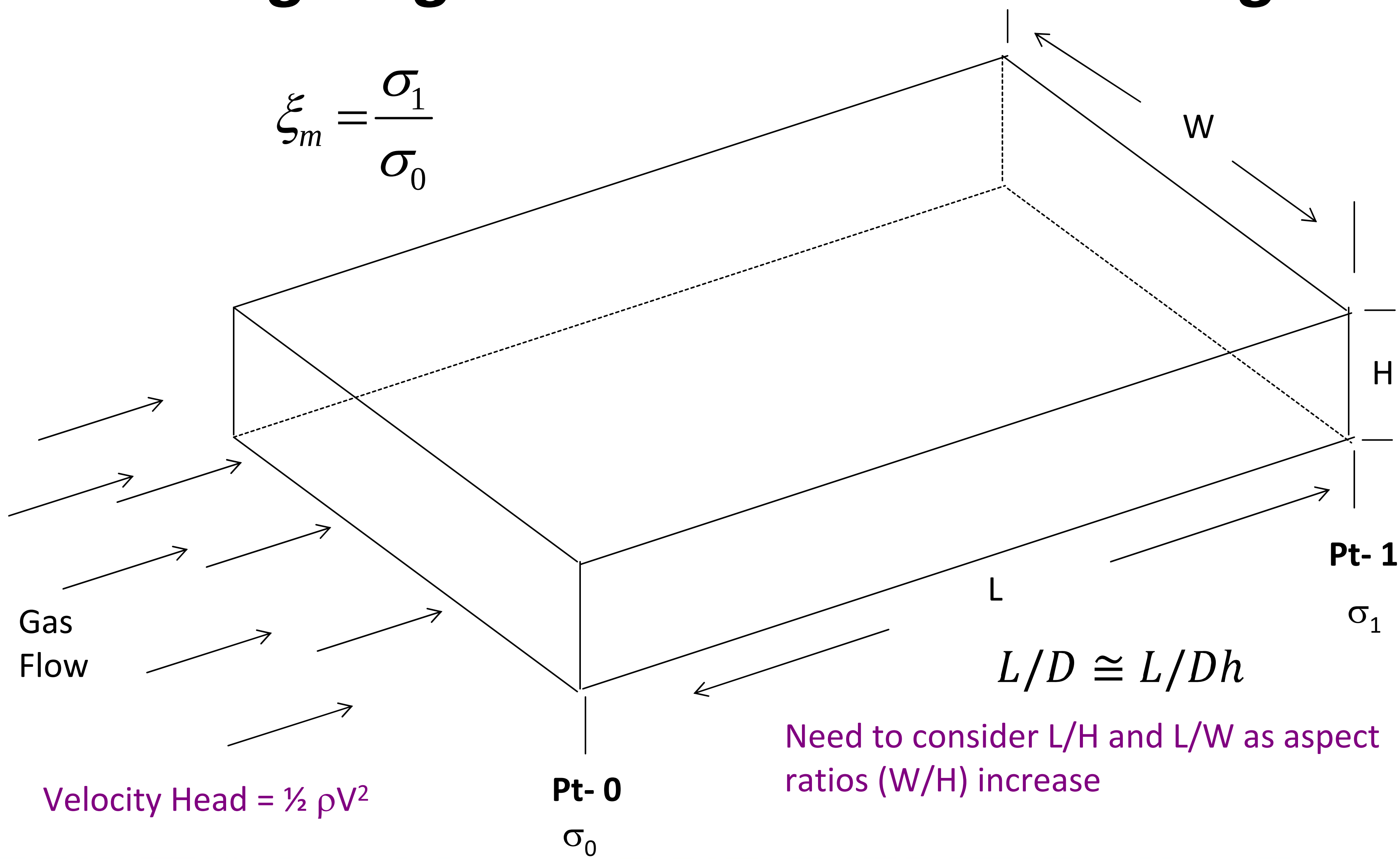
Classical Delta Wing

Ammonia Injection & Mixing Approach



Designing for Whole Duct Blending

$$\xi_m = \frac{\sigma_1}{\sigma_0}$$



$$L/D \cong L/Dh$$

Need to consider L/H and L/W as aspect ratios (W/H) increase

Velocity Head = ½ ρV^2

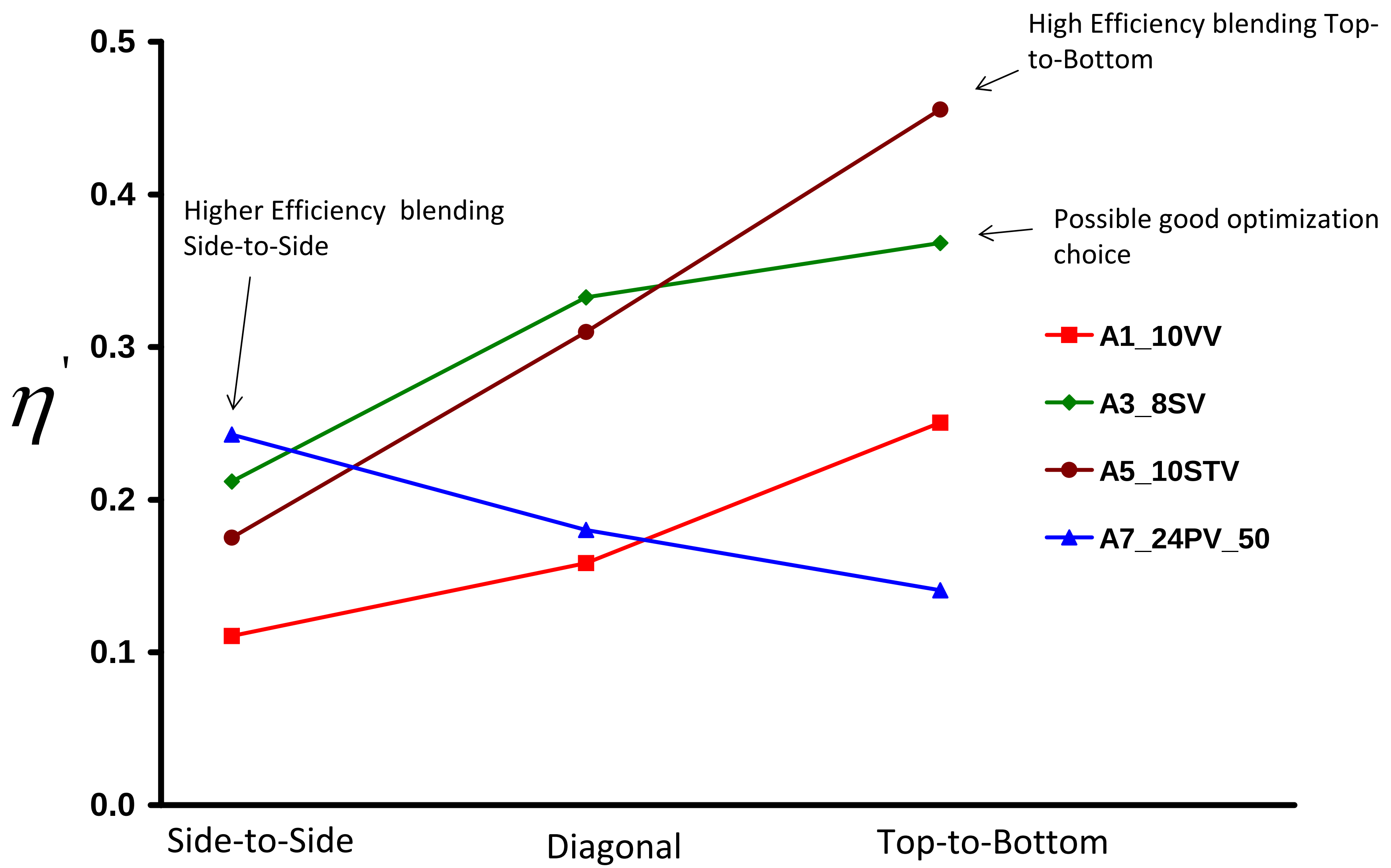
Mixing Effectiveness versus Efficiency

Mixing Effectiveness Parameter $$\xi_m' = 1 - \frac{\sigma_1}{\sigma_0}$$

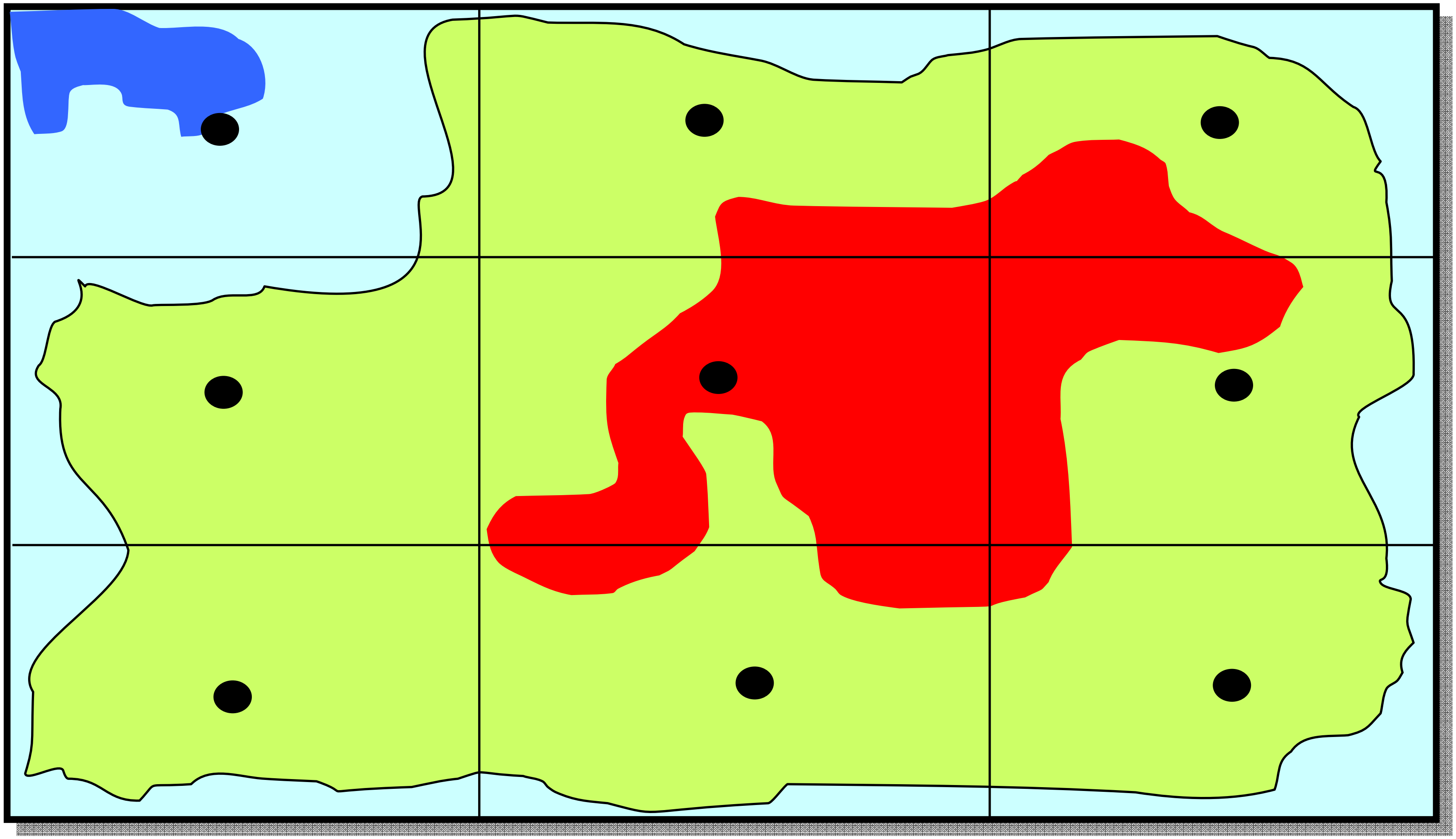
Mixer Shock Loss Coefficient $$\zeta_m = \frac{\Delta P_m}{\rho V^2 / 2}$$

Dimensionless Mixing Efficiency $$\eta_m' = \frac{\xi_m'}{\zeta_m}$$

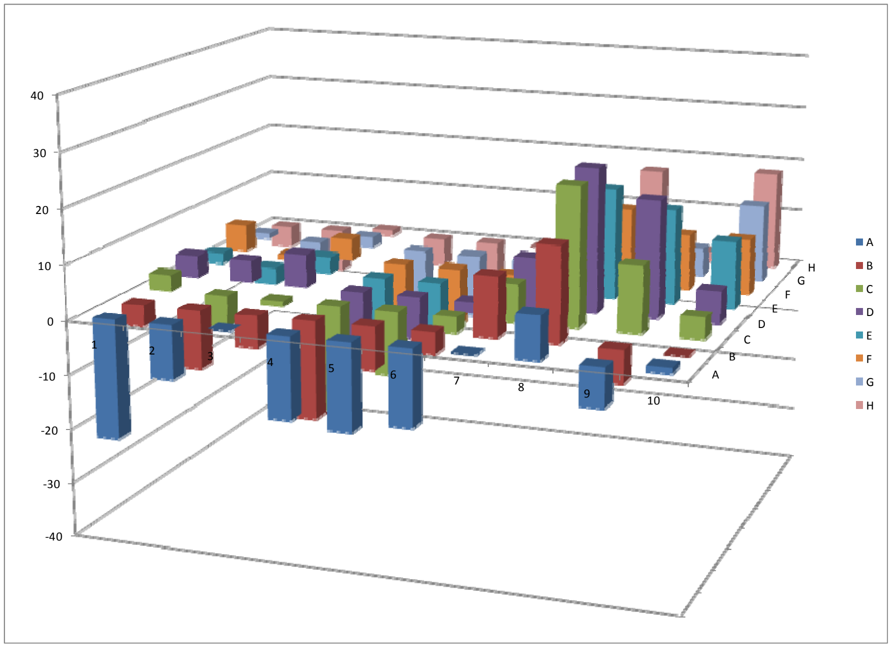
Mixer Efficiency & Directivity



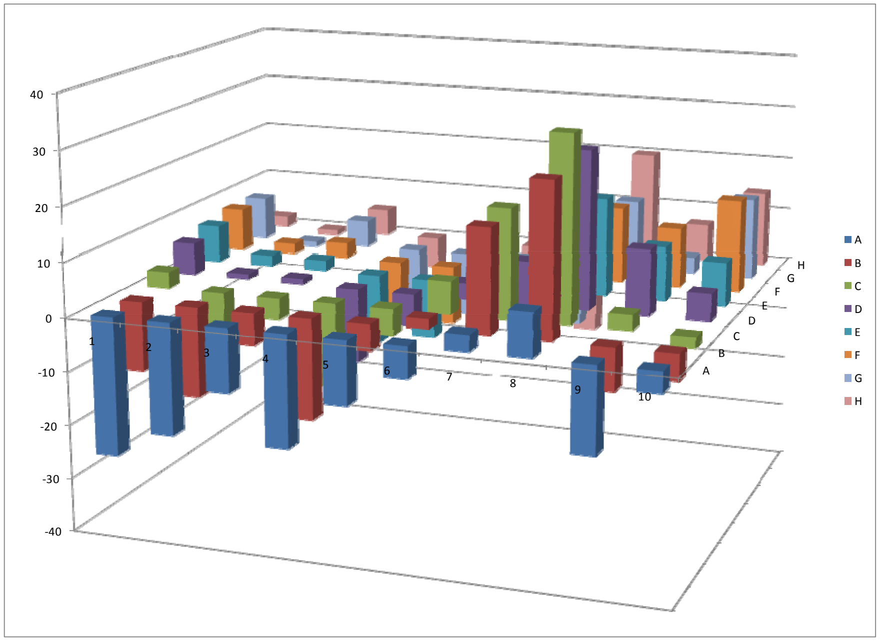
AIG Dosing



Velocity Variation at AIG versus Load

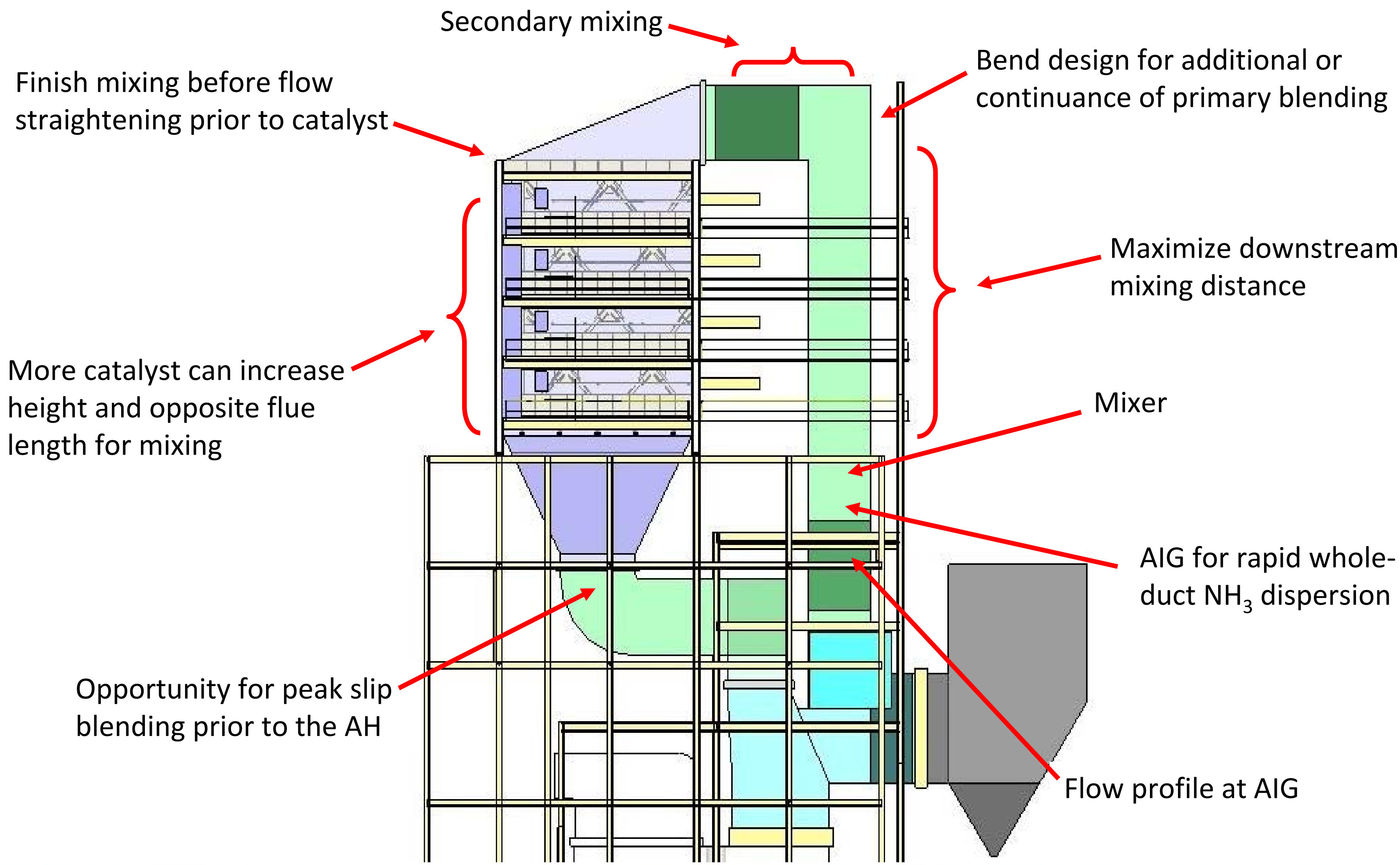


100% Load



40% Load

Arrangements for Promotion of Mixing



Actual Field Uniformity Performance

Field Site →	A	B	C	D	E
Mixer Design	Other	Other	B&W	B&W	B&W
Removal Efficiency, %	87%	86%	92%	93%	89%
SCR Outlet NOx COV	18%	23%	16%	10%	24%
SCR Inlet NH3/NOx COV	2.5%	3.8%	1.9%	1.2%	3.2%
Relative Mix Length	1.5	3.3	1.0	2.7	2.8
Relative Shock Loss	2.0	1.0	2.7	3.3	1.3

Summary

Multiple approaches exist for SCR -

- Appear to be functioning adequately (Some better than expected)
- Only a few reports of plugging (Injection point eddies, support build-up)
- Ammonia injection before primary mixing elements.
- Ammonia injection after primary mixing elements.

Important optimization parameters -

- Initial dosing (AIG design, NO_x profile, flow profile)
- Injection nozzle quantity and size (Influenced by location and mixer design)
- Mixer directivity of mixing – low aspect ratio versus high aspect ratio
- Mixer length efficiency versus energy efficiency
- Arrangement design (Flue size, dampers, expansions, contractions, bends, hoods, by-pass, etc.)
- Specified flow velocity uniformity requirements (Not always compatible with best design)

Summary

Field performance is tracking predicted well

- Effectiveness is being proven and efficiencies are being established
- Verifying non-plugging AIG designs are indeed non-plugging
- Fundamentals remain applicable and are being validated
- Some approaches can become impractical as L/D drops
- Process result limitations can occur at very low L/D
- Turbulent mixer characteristics apply to all turbulent mixers
- Designing for **'Set it and forget it'** tuning
- Avoid over tuning!
- AIG flow profile verification (review model study or traverse of actual)
- Goal is to deliver the best, most stable blend, at the lowest possible energy consumption within a given arrangement
- Research for improved configurations is continuing in support of increasingly stringent demands (high process result and/or poor arrangement)

THANK YOU!

Kevin Rogers
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