Ammonia Injection and Mixing Systems

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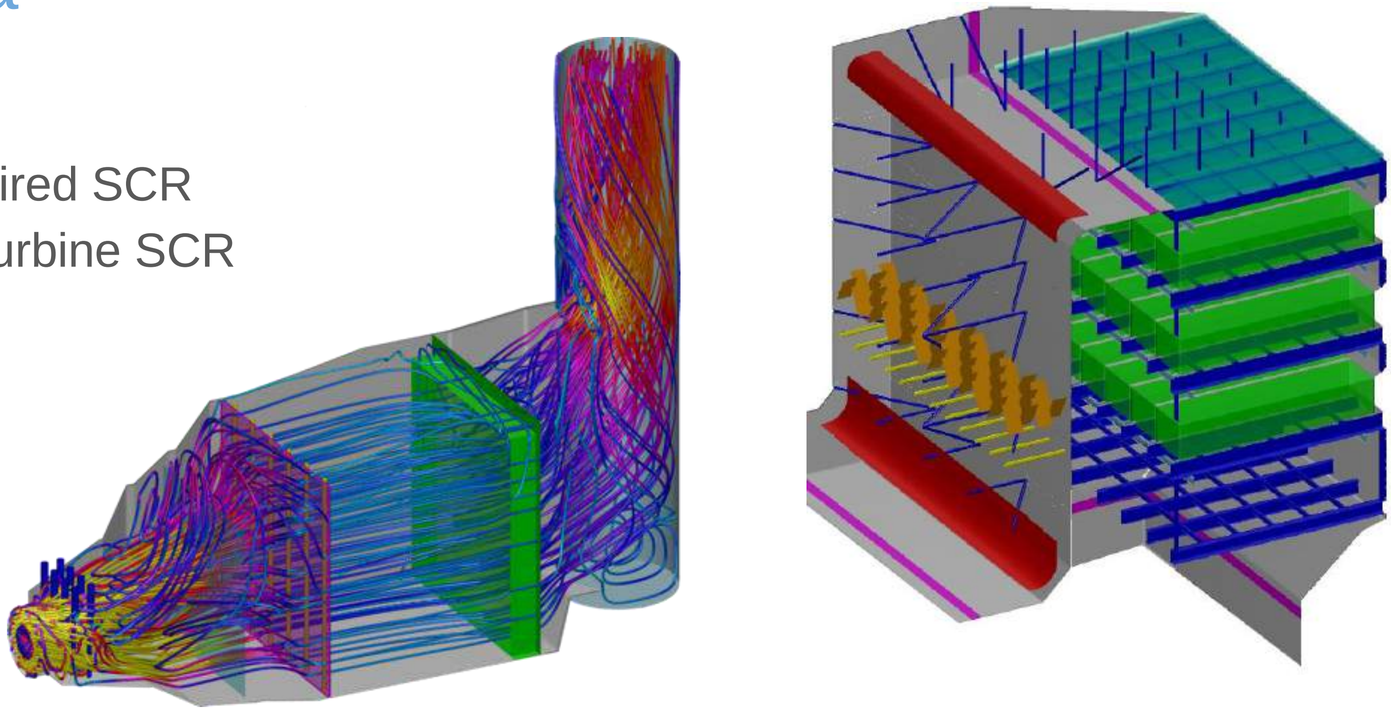
2019 NOx-Combustion-CCR Round Table
February 11, 2019
Salt Lake City, UT

Airflow Sciences Corporation

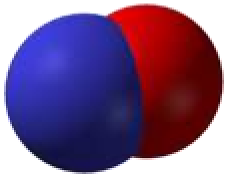
Agenda

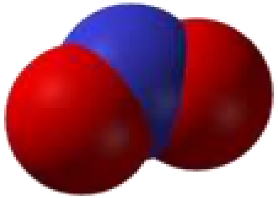
- Intro
- Coal Fired SCR
- Gas Turbine SCR



NOx Control

- Nitrogen oxides – NOx – are important air pollutants by themselves; also react in the atmosphere to form ozone (O_3) and acid rain
- NOx is formed during combustion in the peak temperature zones
- 95% of NOx in the flue gas is initially in the form of NO, rest is NO_2
- Once in the atmosphere, most NOx is converted into NO_2 form
- Typical SCR systems can achieve NOx removal efficiencies over 90%





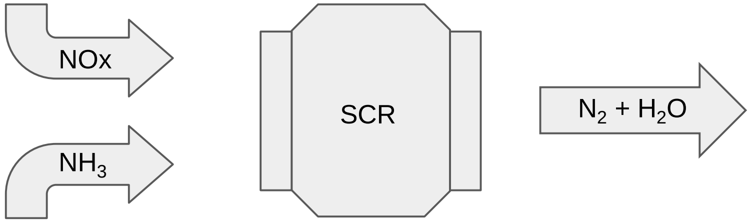
Selective Catalytic Reduction

Selective catalytic reduction (SCR) is a chemical process of using a reductant like ammonia to convert NOx into diatomic nitrogen (N_2) and water (H_2O), with the aid of a catalyst.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$



Ammonia has to react with NOx at the molecular level.

SCR Performance Goals

Performance goals compete with each other:

coal & gas

- Uniform ammonia-to-NOx ratio
- Uniform velocity at AIG
- Unform velocity at the catalyst
- Vertical flow entering catalyst
- Uniform temperature at catalyst
- Minimize pressure loss

coal

- Capture LPA with screen/baffles
- Minimize catalyst pluggage potential
- Minimize erosion potential

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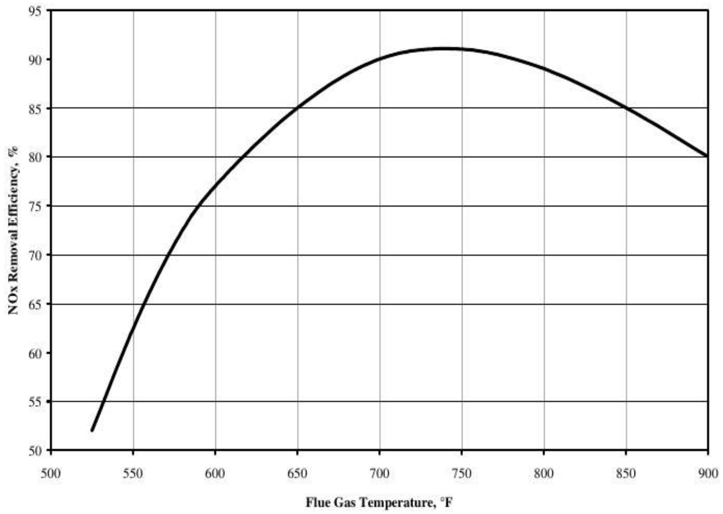
Mixing Priorities for SCR Optimization

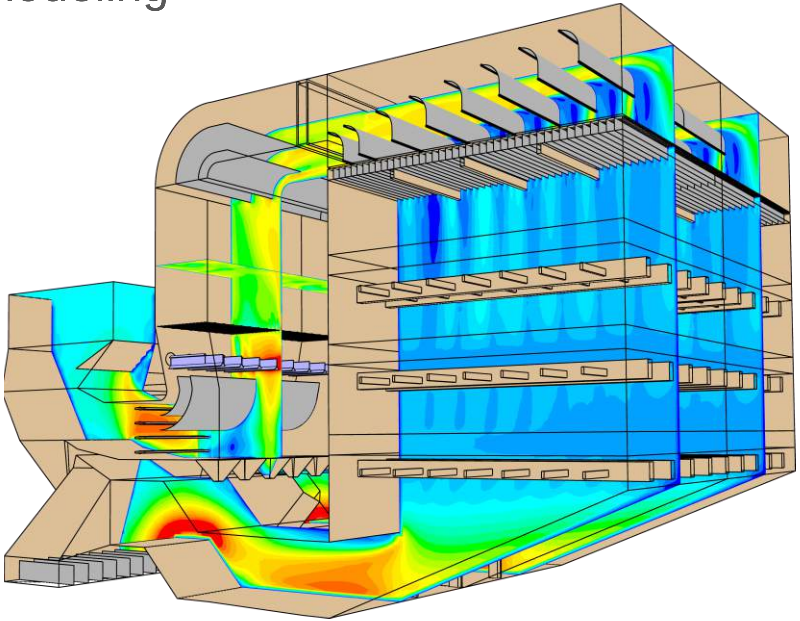
- Ammonia
  - Injection technique plays a key role
- NOx
  - May not be uniform at coal-fired boiler outlet
  - Generally uniform at gas turbine discharge
- Ammonia-to-NOx ratio
  - Must be uniform to maximize deNOx performance and minimize ammonia slip
- Temperature
  - SCR reactions occur optimally within a specific temperature range



NOx Removal Efficiency vs Temperature

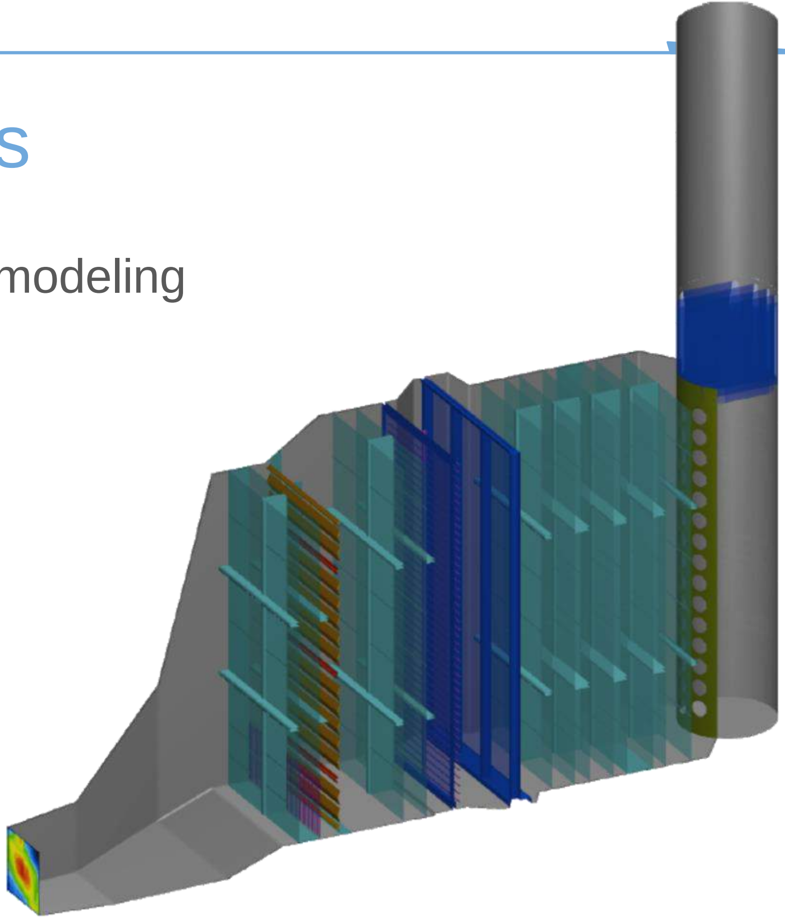
Mixing System Design

- Computational Fluid Dynamics (CFD) modeling
- Physical flow modeling



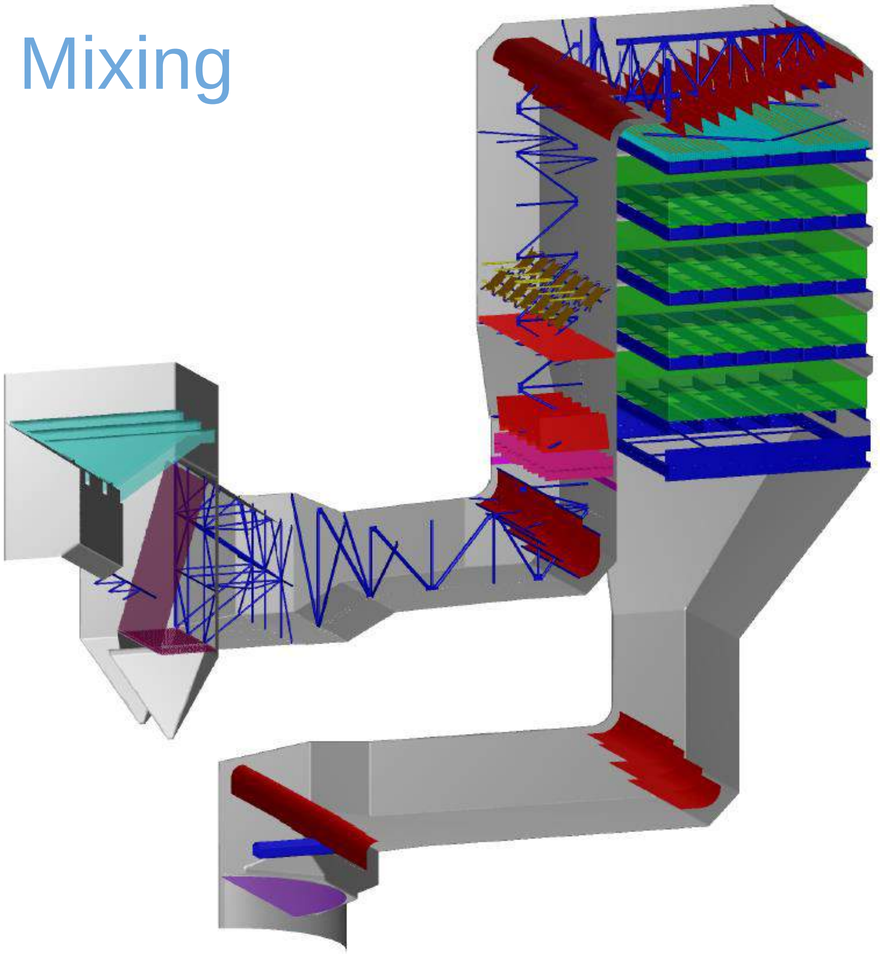
Mixing System Design Tools

- Computational Fluid Dynamics (CFD) modeling
- Physical flow modeling



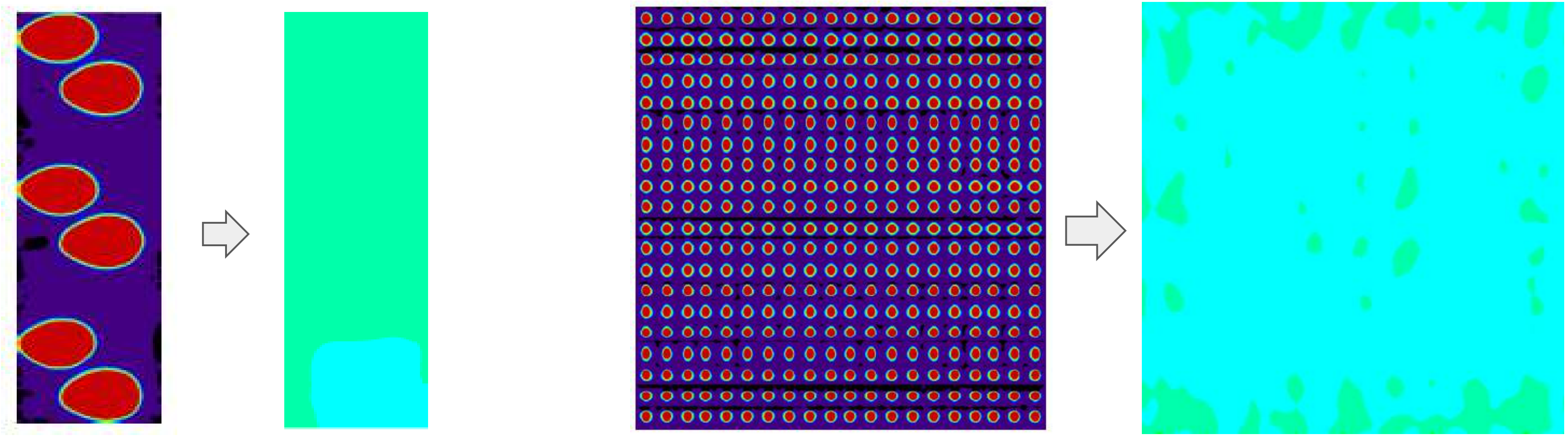
Influences on Ammonia Mixing

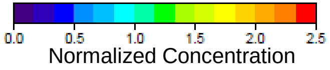
- Ammonia injection technique
  - Nozzle design, location, quantity
- Residence time, diffusion
- General turbulence
  - Elbows, trusses
- Static mixers
  - Induced turbulence
- Negatives to mixing
  - Vanes, rectifiers, straighteners, gas laning
  - CO catalysts, tube banks



Ammonia Injection Grid Design

- Two basic strategies are used for the ammonia injection grid (AIG)
  - Coarse grid of injection points with large mixers
  - Dense grid of injection points, optional local mixers





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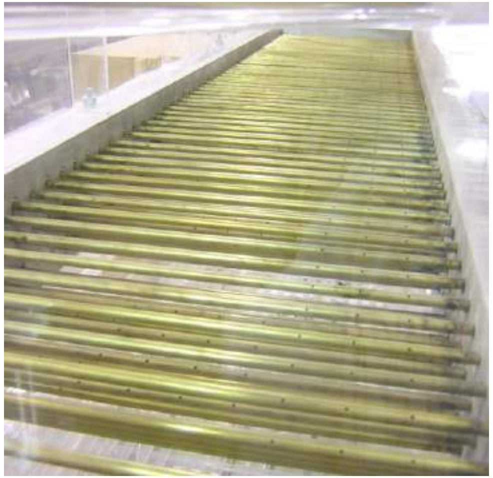


Dense Grid Ammonia Injection

- Many injection lances with multiple nozzles per lance
    - Depending on SCR size, could have 50-100 lances per reactor
    - Numerous nozzles per lance, 10+
    - Often has thousands of discrete injection points
- Either no mixer or only a “local” mixer
- Lances grouped into zones for tuning
- Benefits of dense grid injection
    - More tunable for maximum NOx reduction
    - No negative influence on velocity or flyash distribution at catalyst
    - Lower pressure drop

Dense Grid AIG Issues

- Pluggage of nozzles
- Requires very good velocity profile at AIG location
- Tuning not as predictable as sometimes envisioned
  - Velocity distribution issues
  - Unequal flow per nozzle
  - Low resolution of reactor outlet sample grid
- Valve issues over time

Coarse Grid Ammonia Injection

- Fewer injection lances compared to dense grid by factor of 5-10
  - Depending on SCR size, could have 5, 10, 20 lances per reactor
  - Some systems have just 1 injection point per lance
  - Others have multiple nozzles per lance (2 to 10)
- Lances located immediately upstream or downstream of a static mixer
- Often multiple stages of static mixers
- Benefits of coarse grid injection
  - Fewer nozzles and larger openings less prone to pluggage
  - Mixing and high turbulence reduces sensitivity of gradients
    - Does not need as much tuning?
    - More consistent performance over the load range

Coarse Grid AIG Issues

- Higher pressure loss
- Duct wall and internal structure erosion
- Ash accumulation on mixers
- Tuning not as straightforward due to purposeful creation of turbulence

Vaporized Ammonia Injection vs Direct Injection

- Vaporized Ammonia Injection
  - utilizes vaporizer skid to get ammonia into gaseous form prior to injection
  - need to ensure ammonia properly vaporized and mixed with dilution air
  - more common but higher capital cost
- Direct Injection
  - inject aqueous ammonia directly in liquid form without dilution air or vaporization
  - relies on heat from flue gas for vaporization
  - requires special spray nozzles to insure proper vaporization and mixing
  - concern about liquid ammonia impingement on walls, mixer

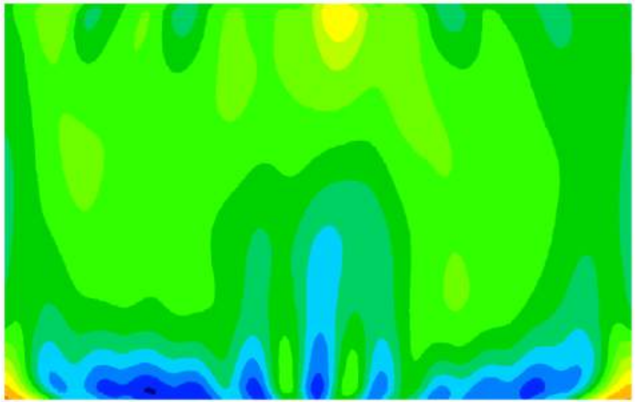
Coal Fired SCR Performance Goals

Performance goals compete with each other:

- Uniform ammonia-to-NOx ratio
- Uniform velocity at AIG
- Unform velocity at the catalyst
- Vertical flow entering catalyst
- Uniform temperature at catalyst
- Minimize pressure loss
- Capture LPA with screen/baffles
- Minimize pluggage potential
- Minimize erosion potential

Ammonia-to-NOx Ratio

- Ammonia-to-NOx ratio at the catalyst inlet plane should be “uniform”
- Allows optimal NOx reduction with minimum ammonia slip
- Typical goal is %RMS < 5% or a deviation within +/-5% of mean
- Can be highly influenced by velocity patterns

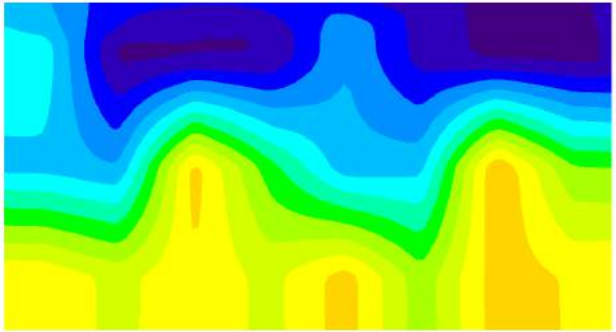


Poor Distribution

Better Distribution

NOx Stratification

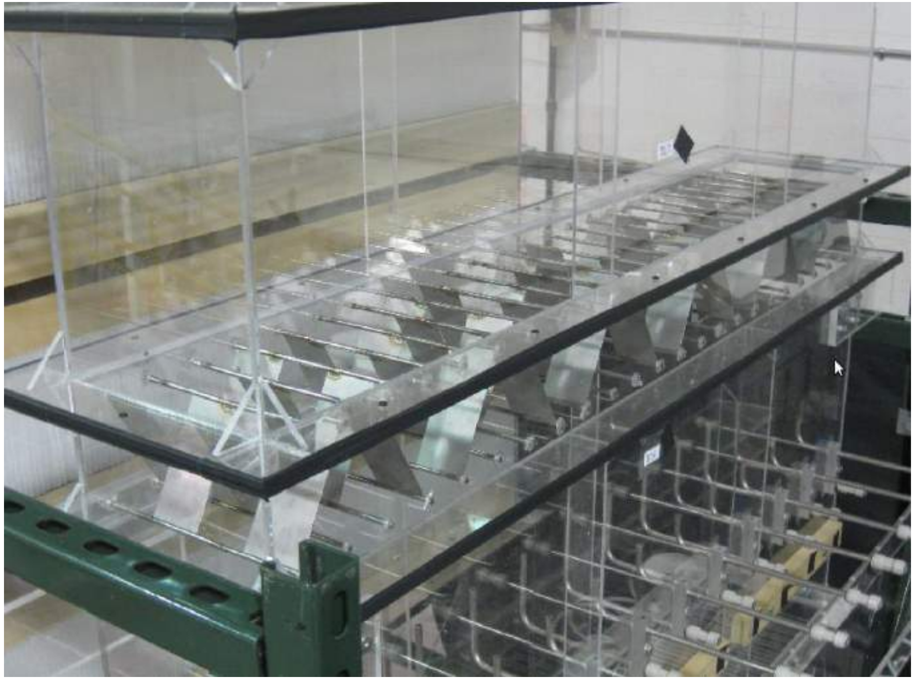
- NOx is not necessarily uniform at the boiler exit; it is a function of
  - Boiler design
  - Burner air flow balance
  - Coal pipe balance
  - Mills out-of-service
- Solutions
  - Tune the NH_3 to the NOx profile
    - Consistency over load range important
  - Mix the NOx prior to the NH_3 injection – “Pre-mixer”
  - Mix the NOx and the NH_3 – one or more stages of mixing



Example of NOx Profile at Economizer Outlet

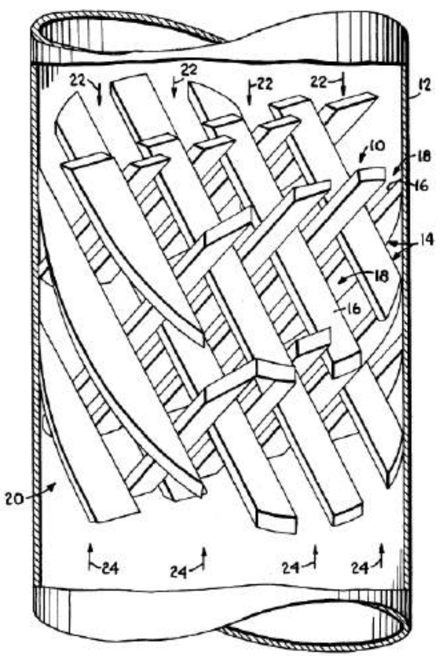
Types of Mixers

- Shear Mixers
- Swirl-Shear Mixers
- Vortex Mixers

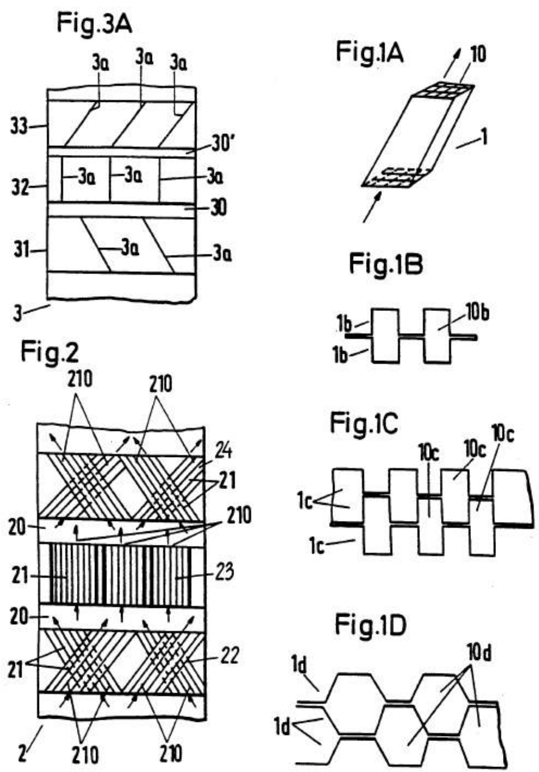


Shear Mixers

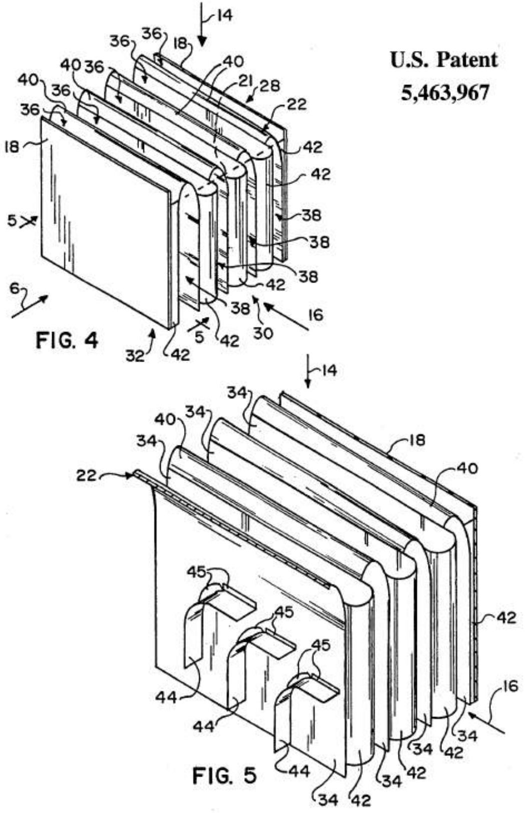
U.S. Patent US 6,224,833 B1



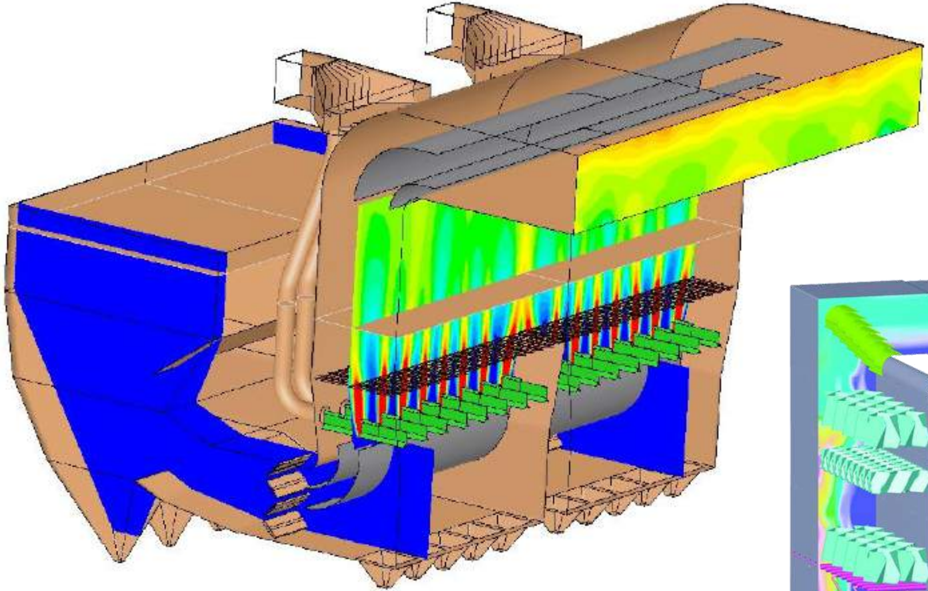
U.S. Patent 5,320,428

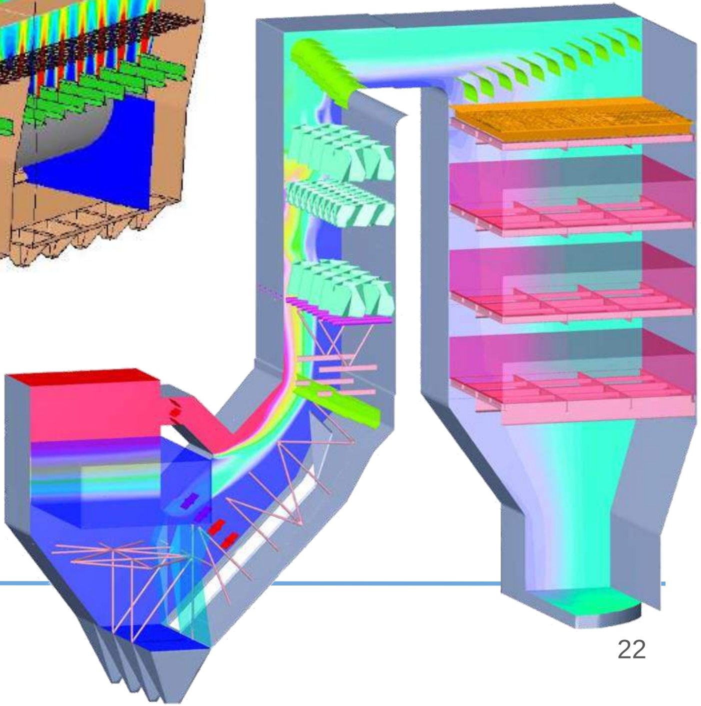


U.S. Patent 5,463,967

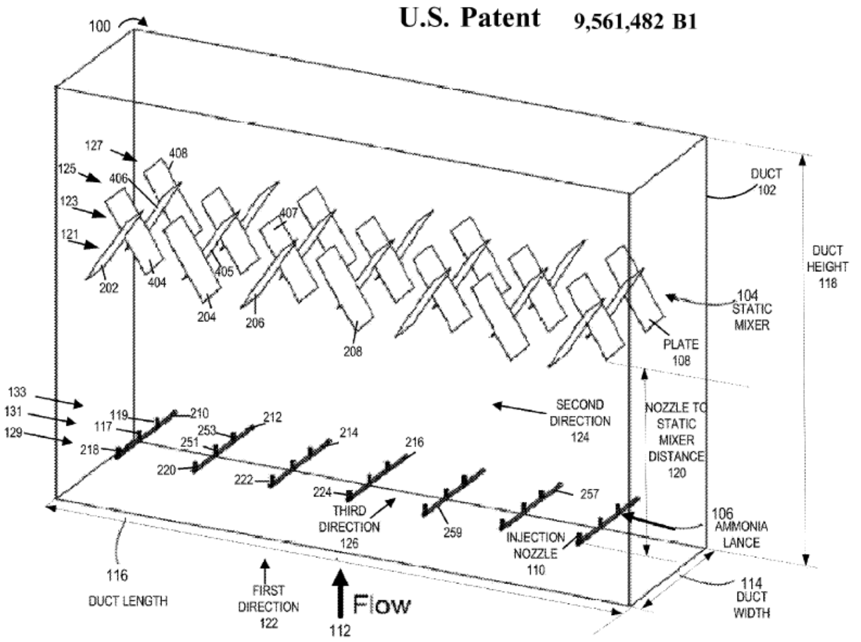


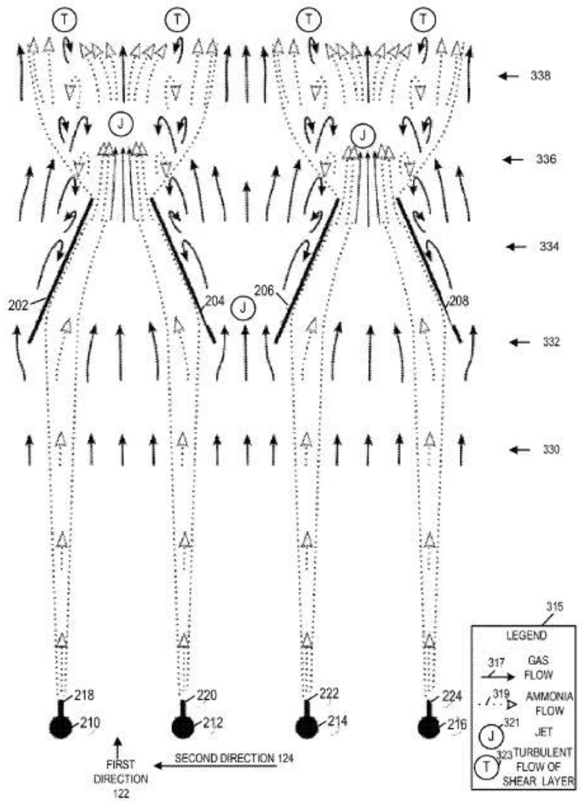
Shear Mixers



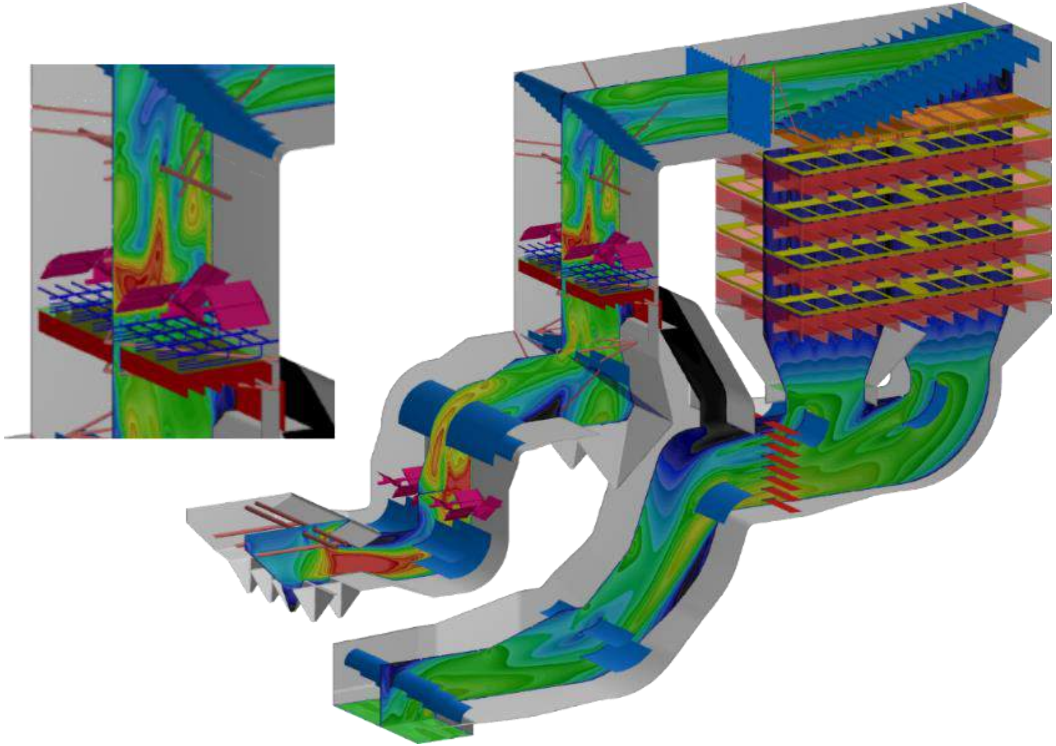


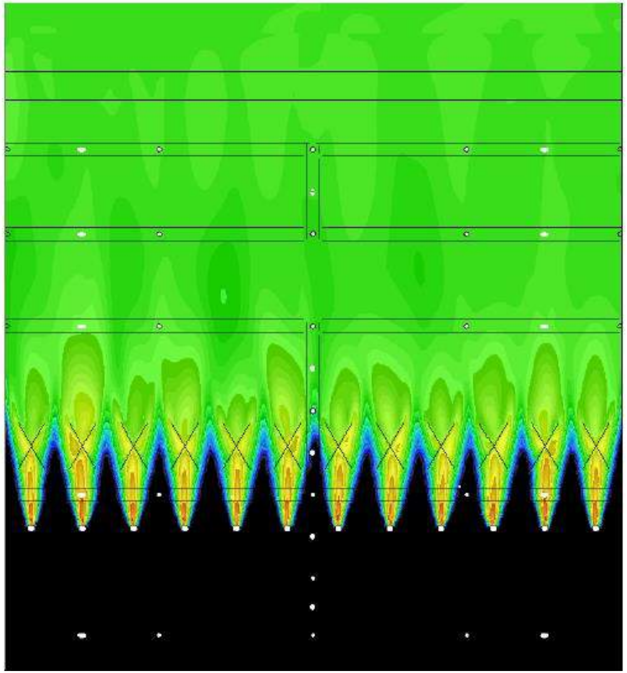
Swirl-Shear Mixers



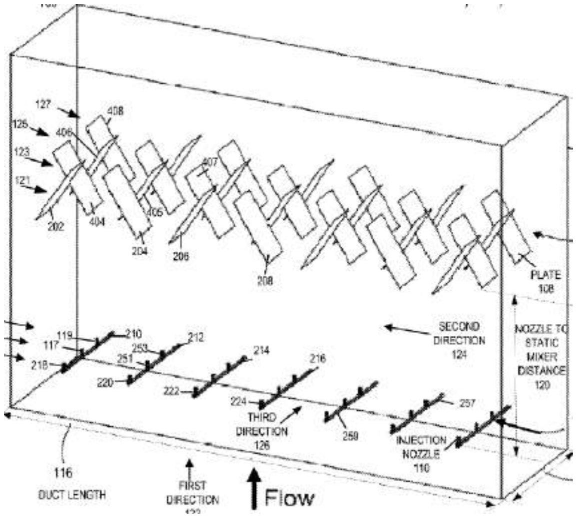


Swirl-Shear Mixers





Swirl-Shear Mixers



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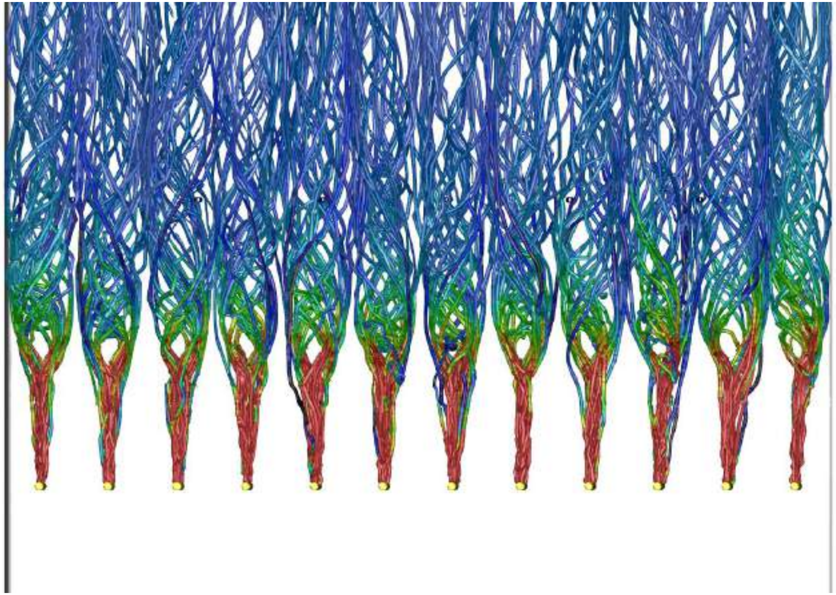
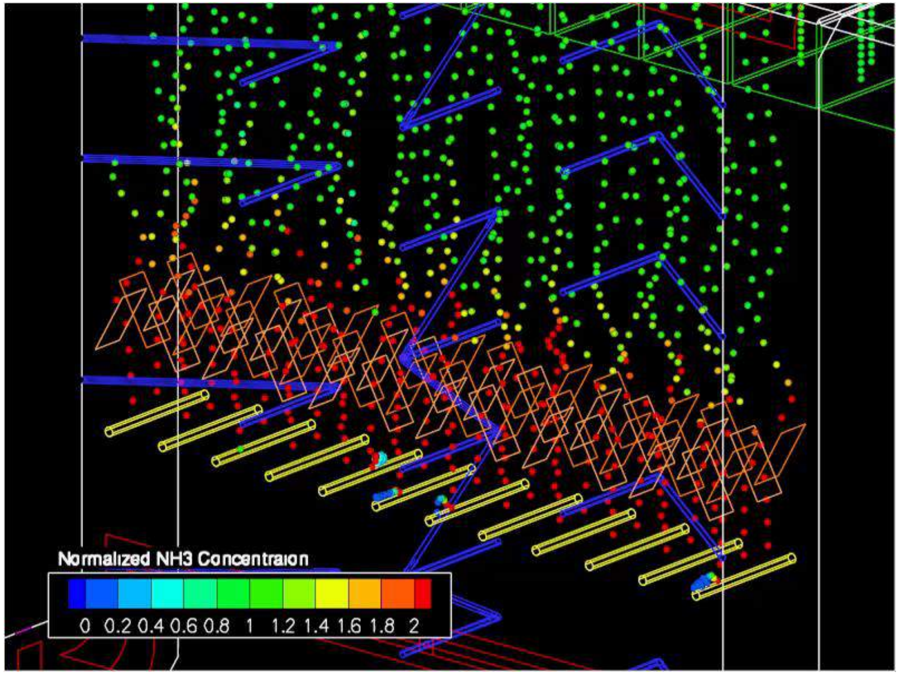
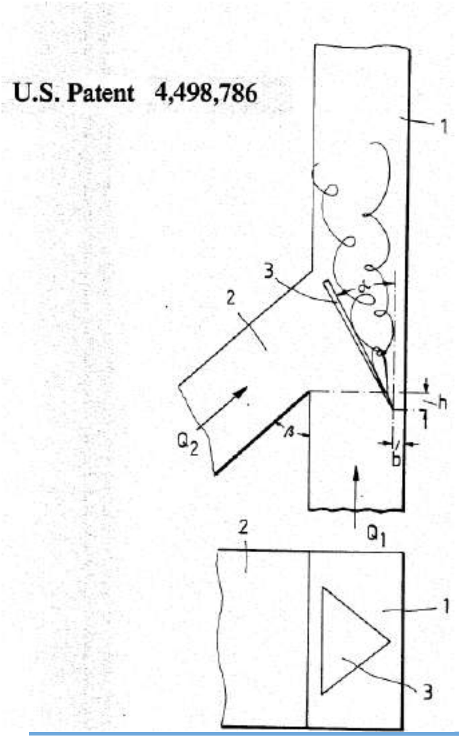
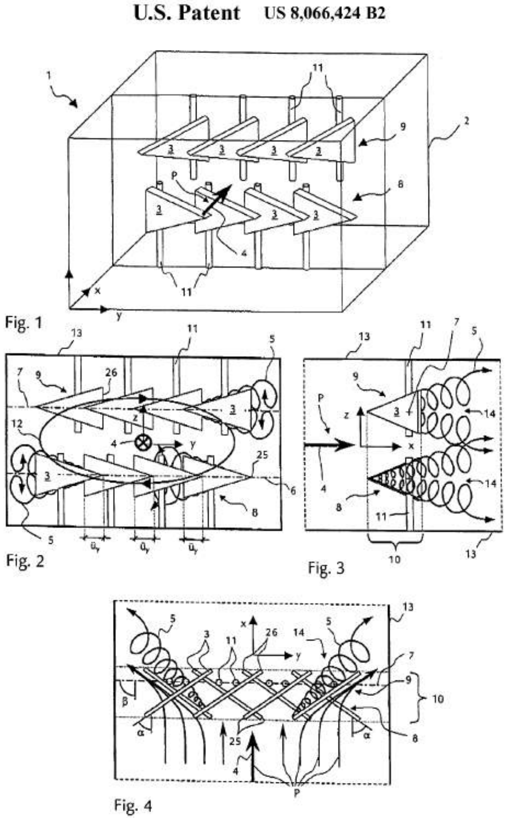
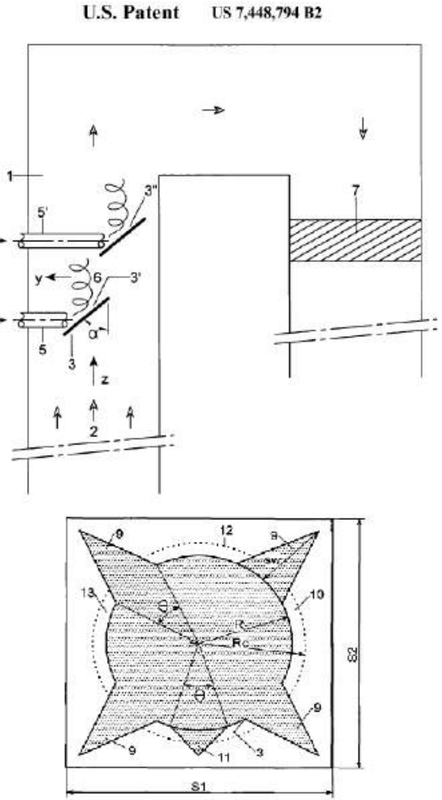




Vortex Mixers







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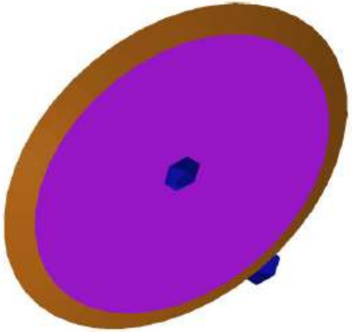
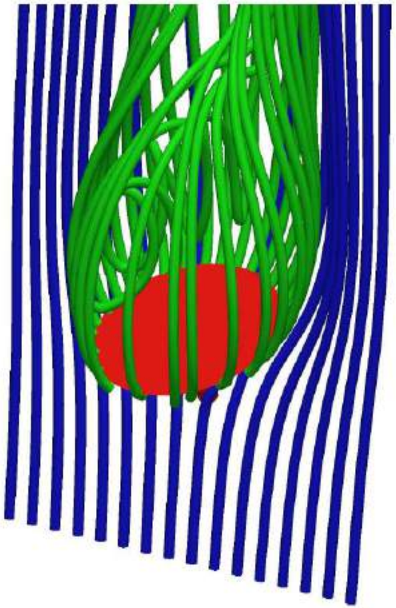
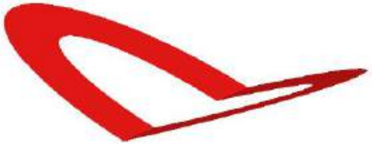

Geometry


Fluid path lines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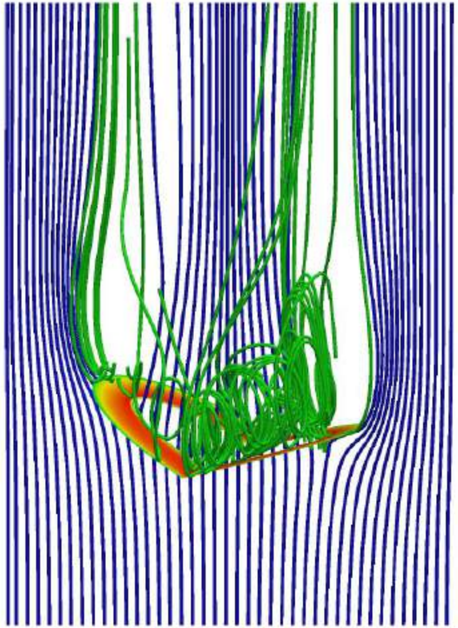
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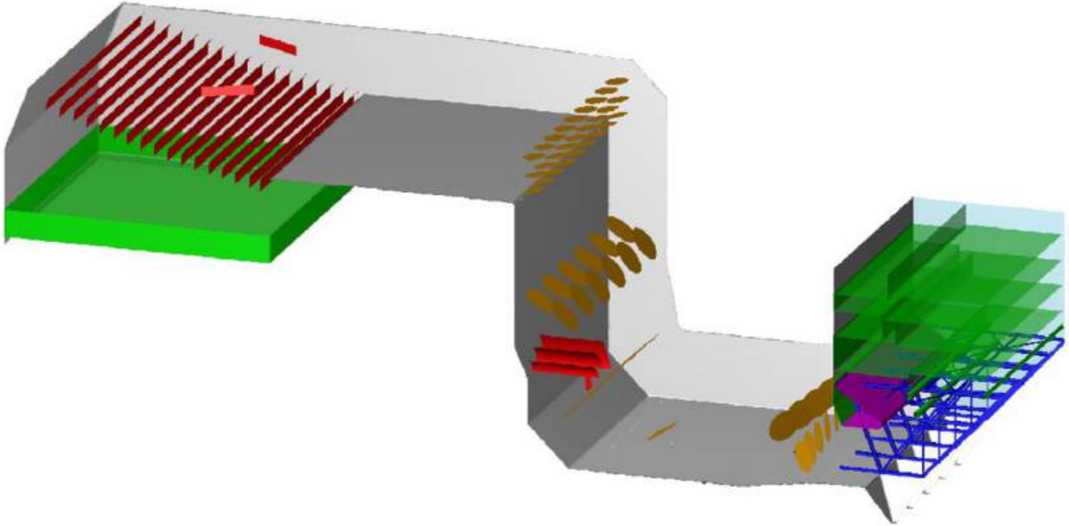
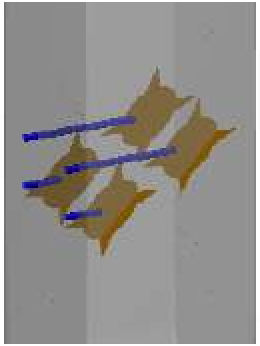
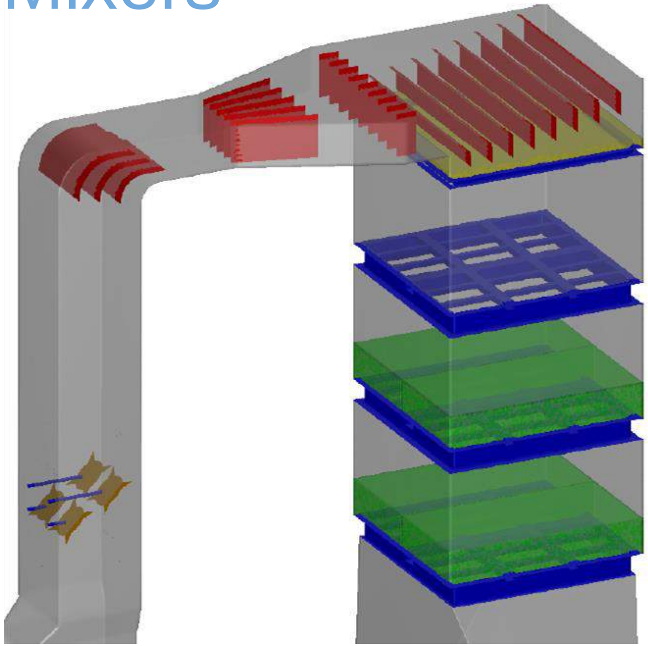
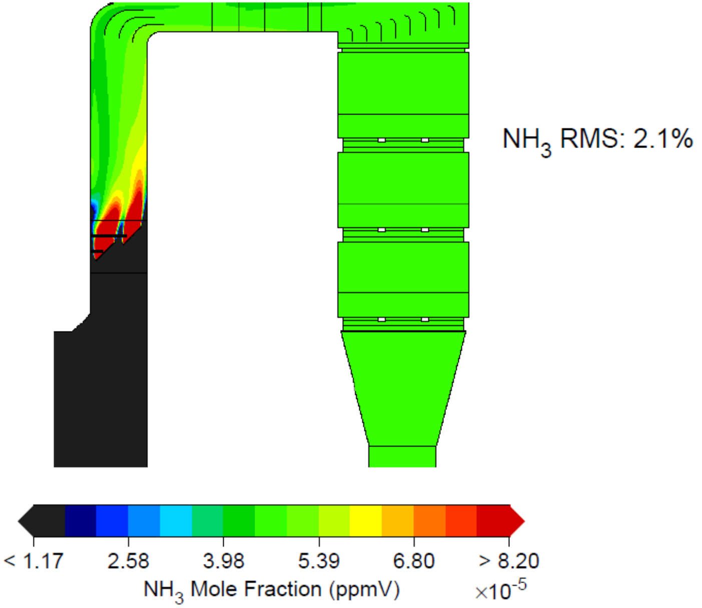
Vortex Mixers

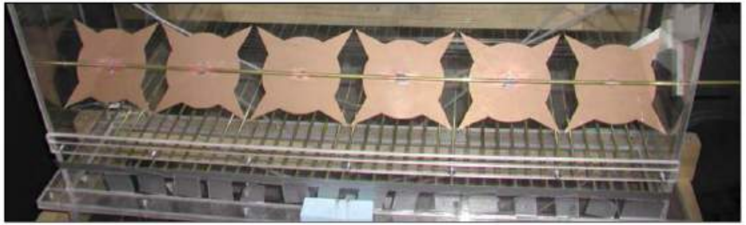


Vortex Mixers



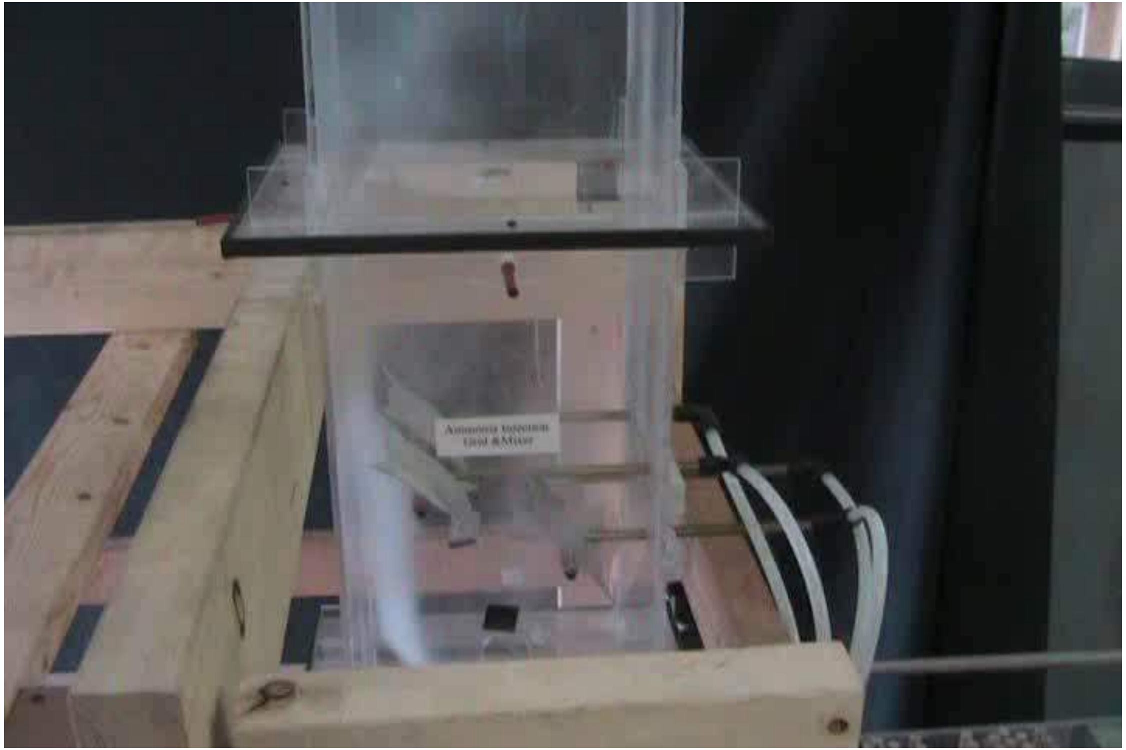






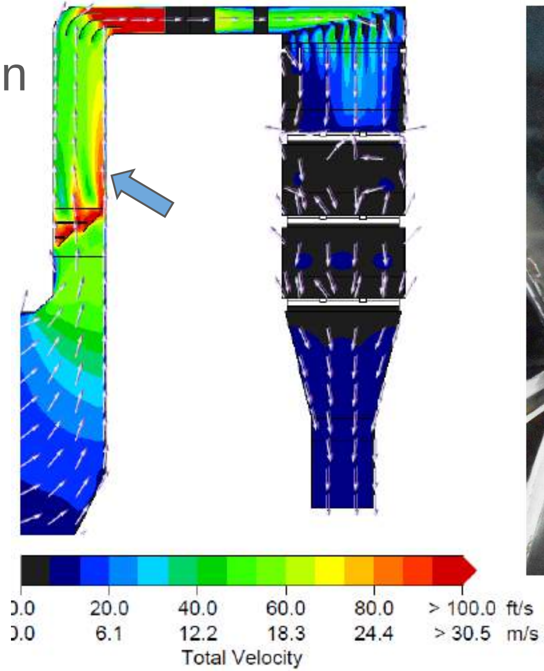
Courtesy Haldor Topsoe

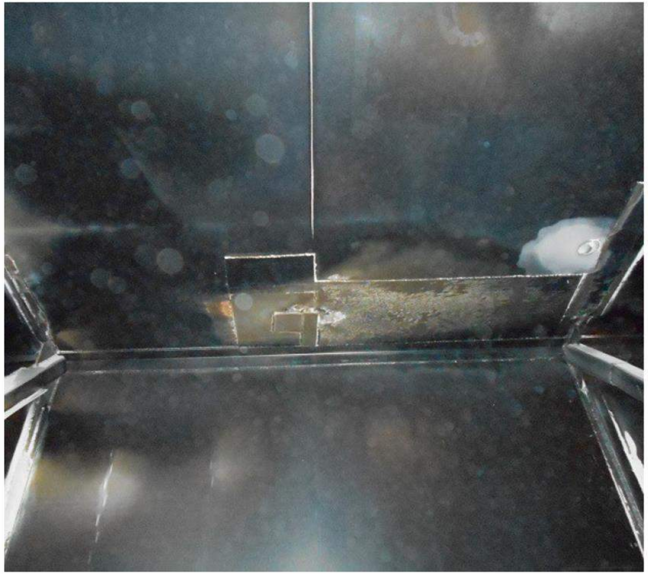
Vortex Mixers



Mixer Issues

Erosion





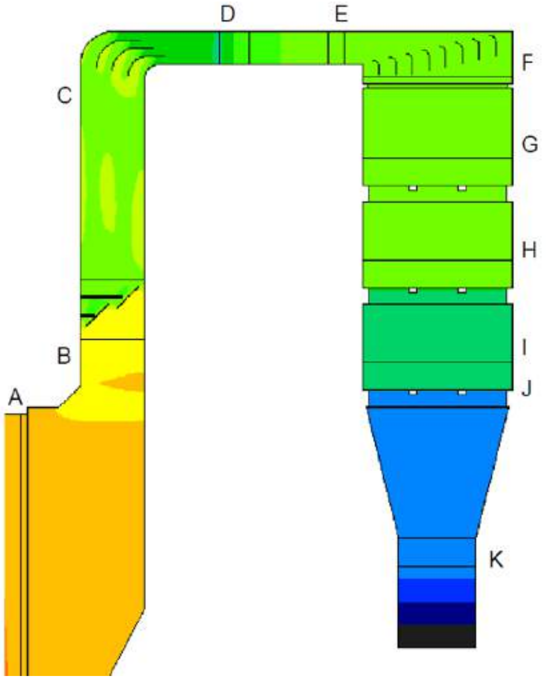
Mixer Issues

Pressure Drop

	Location	Total Pressure Loss (inH2O)	Total Pressure Loss (mmH2O)
A	Evaporator Outlet	0	0
B	Upstream AIG	-0.03	-0.8
C	Downstream AIG	-0.75	-19.1
D	Upstream SCR Duct Expansion	-0.95	-24.1
E	Downstream SCR Duct Expansion	-1.07	-27.1
F	Upstream Flow Rectifier	-1.23	-31.2
G	Upstream (Future) 1st Catalyst Layer	-1.26	-32.1
H	Upstream 2nd Catalyst Layer	-1.29	-32.7
I	Upstream 3rd Catalyst Layer	-2.30	-58.3
J	Downstream 3rd Catalyst Layer	-3.29	-83.7
K	Economizer Inlet	-3.31	-84.0
A-K	**Total DP, Evaporator Outlet to Economizer Inlet**	**3.31**	84.0
A-K	**Total DP, Excluding Catalyst Layers**	**1.27**	32.3

DP = 0.72 IWC

Typical mixer stage
DP = 0.3 to 0.8 IWC

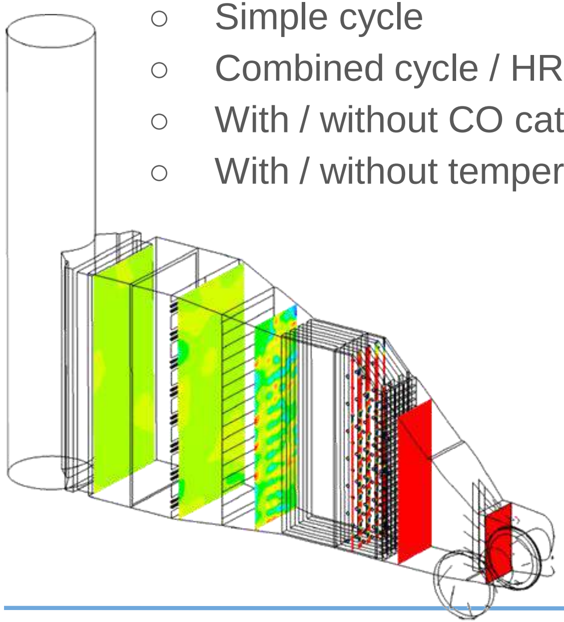


Summary – Coal Fired SCR

- NH_3, NOx, and temperature distributions are key players in SCR performance
- Pre-mixer often used for NOx and temperature at boiler outlet
- Dense Grid injection generally no mixer or “local” mixer
- Coarse Grid injection will have 1 or more high turbulence mixer layers
- Ammonia injection and mixer design involves many competing criteria which must be understood and optimized

Gas Turbine SCR

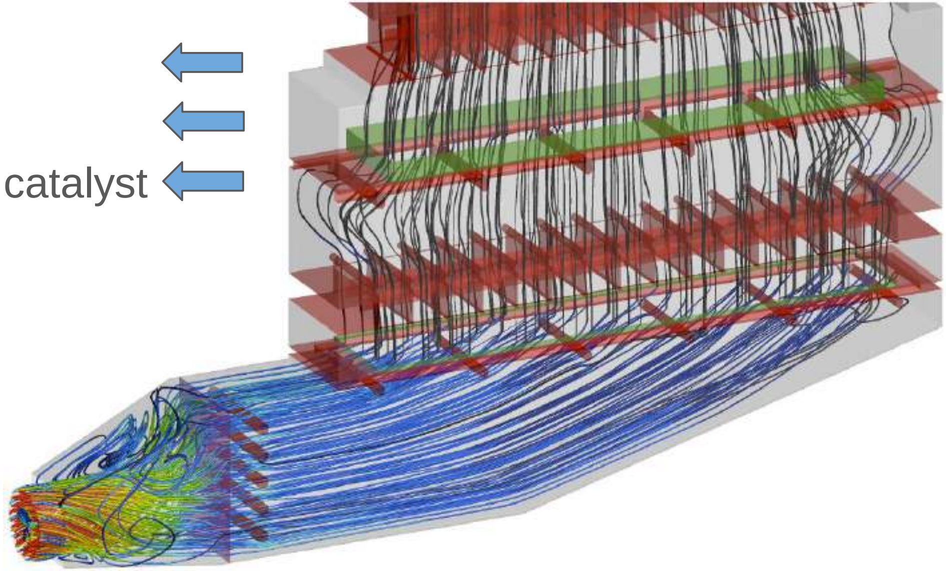
- Gas turbine systems come in many sizes and flavors
  - Simple cycle
  - Combined cycle / HRSG
  - With / without CO catalyst
  - With / without tempering air



Gas Turbine SCR Performance Goals

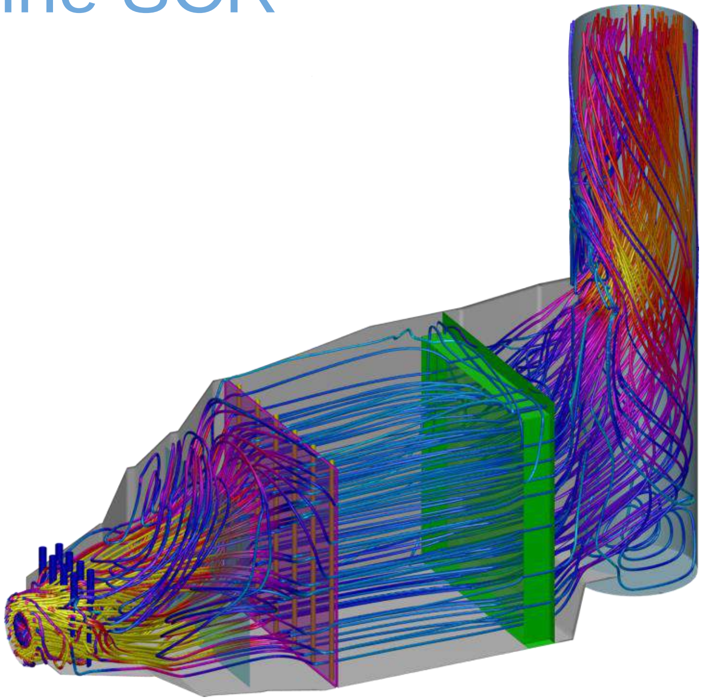
Typical performance goals compete with each other:

- Uniform ammonia-to-NOx ratio
- Uniform velocity at AIG
- Uniform velocity at CO and SCR catalyst
- CO catalyst influence on SCR
- Uniform temperature at catalyst
- Minimize pressure loss



Flow Distribution in Gas Turbine SCR

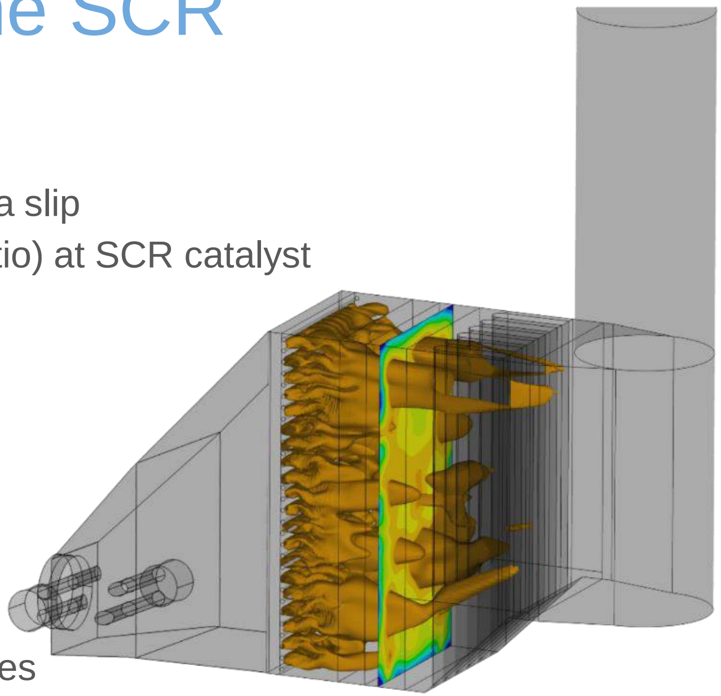
- Gas Flow Through System
  - Uniform velocity profile (15% RMS or better) at
    - CO/NOx/Dual Action Catalyst
    - AIG
    - Tube banks
- Not easy given that the inlet condition resembles a tornado
- Requires intricate design of flow devices
  - Baffles
  - Straighteners
  - Perforated plates



Flow Streamlines in a HRSG CFD model

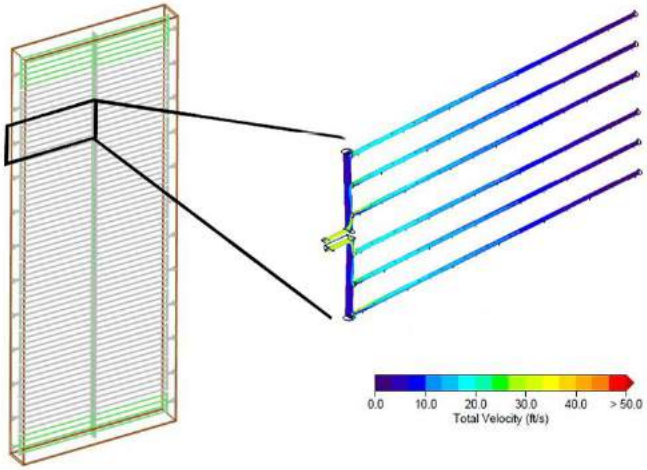
Ammonia Injection in Gas Turbine SCR

- Design considerations for ammonia injection
  - The key factor in deNOx performance and ammonia slip
  - Goal is uniform concentration (ammonia-to-NOx ratio) at SCR catalyst
  - General target is 10% RMS or better
  - Optimization requires balance of competing goals
    - Velocity profile at AIG & SCR catalyst
    - Pressure drop
  - AIG design is not straightforward
    - Residence time for mixing is limited
    - Temperature heat up can affect distribution
    - Updated design practices have led to advances
    - Older systems likely have room for improvement



Ammonia Injection Grid

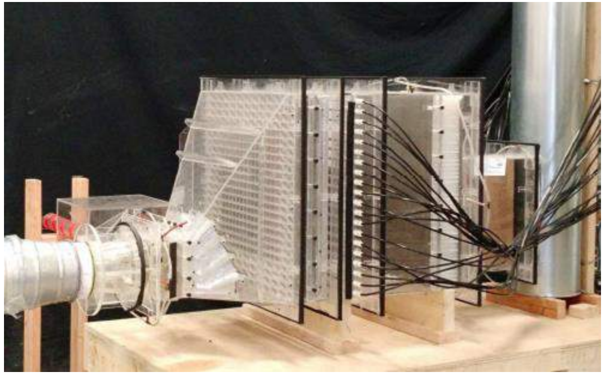
- AIG Design:
  - General goal is to inject equal ammonia from each nozzle to within 2% or better
  - Correct sizing of header ID, lance ID, and nozzle diameters is important
  - Need to consider heat transfer from gas side to the internal pipe flow; this can influence the balance between nozzles
  - The presence of tuning valves cannot always fix a poor AIG header/lance design



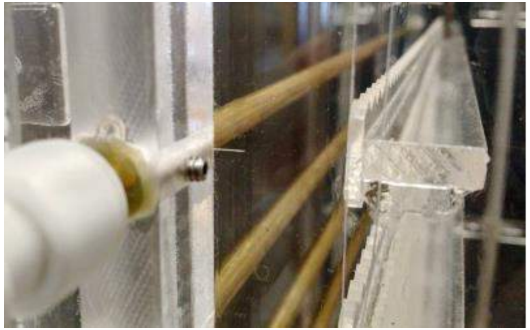
Flow Modeling of AIG header and lances

Ammonia Injection Grid

Ammonia Distribution at SCR

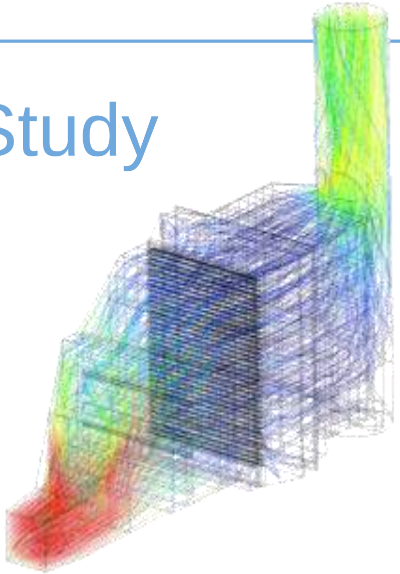


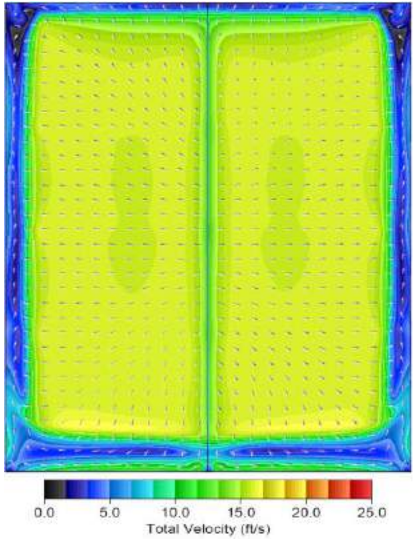
- Need to ensure sufficient number of lances/nozzles to cover the cross section
- Depends on residence time to catalyst and turbulence intensity
- Additional mixing may be required depending on geometry details
  - Static mixer after AIG
  - Turbulence generators integrated with AIG
- Modeling and testing to guide design



AIG Optimization Case Study

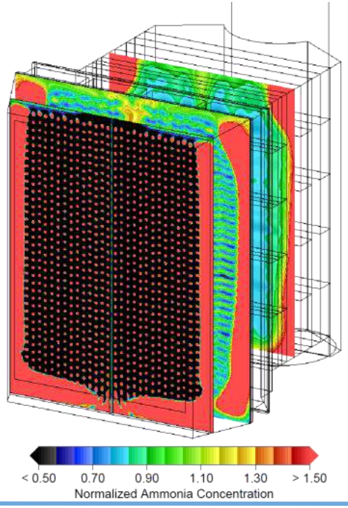
- HRSG unit struggling with poor ammonia distribution at the SCR catalyst and high ammonia slip.
- Plant AIG tuning was not successful, could not eliminate high ammonia gradients near walls
- CFD model corroborated field data showing velocity profile at the AIG having large areas of low flow or recirculation.
- NH3 slip results in fouled tubes

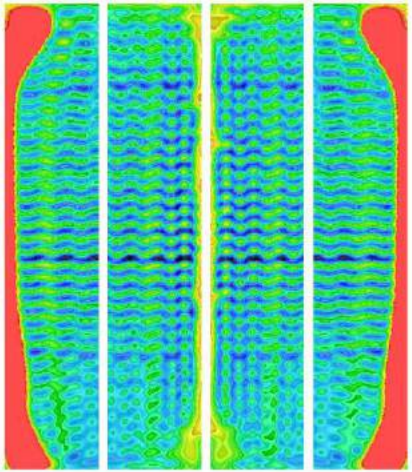


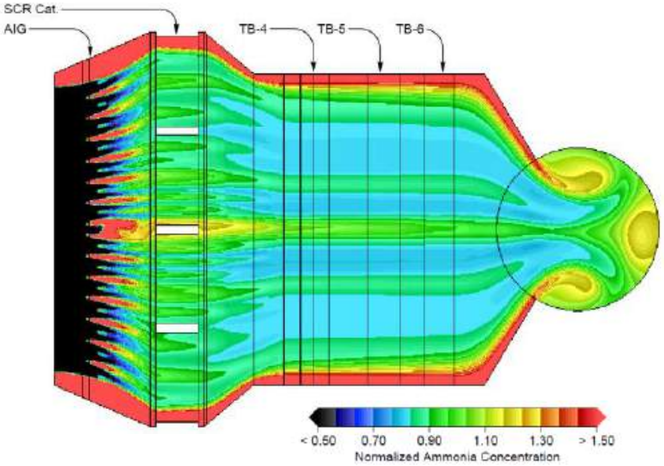


AIG Optimization Case Study

- CFD model indicates very high ammonia concentrations near the walls of the unit.
- Ammonia RMS of 59% at the SCR catalyst face.

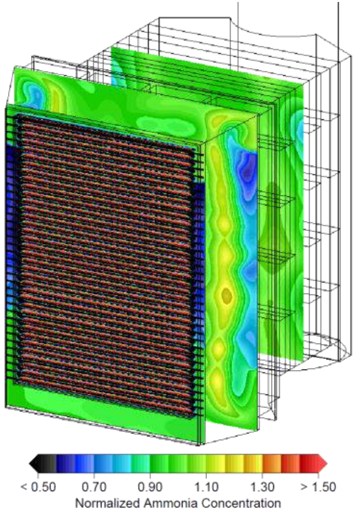


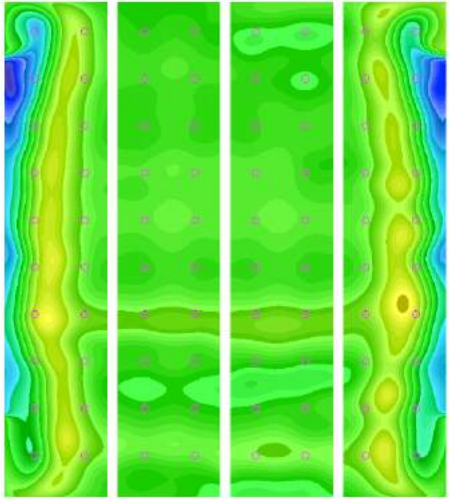


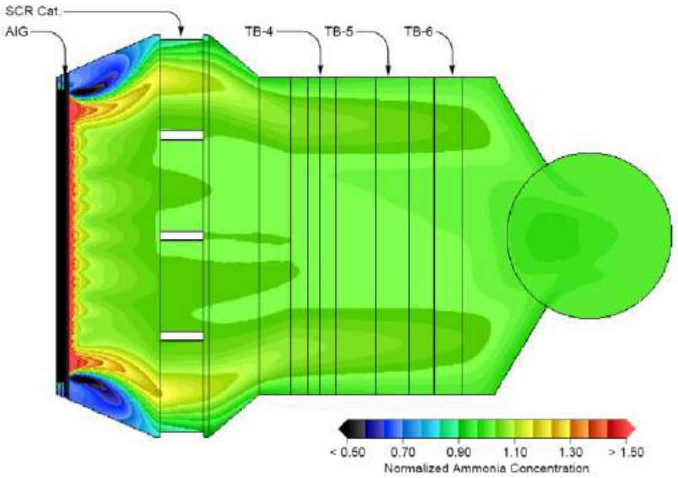


AIG Optimization Case Study

- AIG modifications added to improve local mixing and ammonia distribution
- Ammonia RMS improved to 8% at the catalyst face







Summary – Gas Turbine SCR

- There are many parameters that affect gas turbine and SCR performance
- AIG design involves many competing criteria which must be understood and optimized
- Residence time is usually quite limited in gas turbine SCR; local mixer may be necessary
- Need optimized design at beginning, and design improvements over time
- Cost-effective enhancements are possible to existing systems

Questions & Contact Information

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