REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table
& Expo Presentation

February 19-20, 2018, in St. Louis, MO / Hosted by Dynegy

BLENDER PRODUCTS, INC

OPTIMIZATION OF DIRECT INJECTION OF AQUEOUS AMMONIA ON CCGT POWER STATIONS

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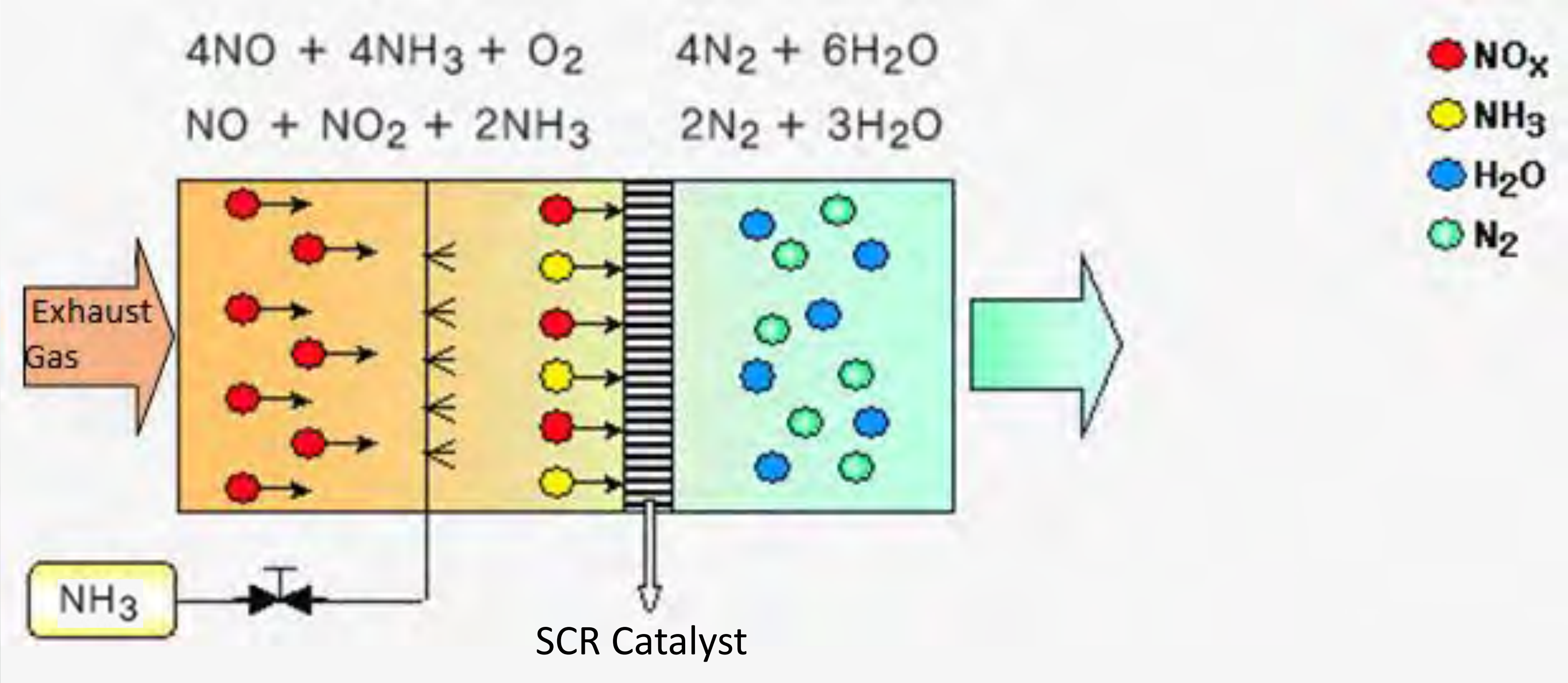
FEB 20, 2018

Engineered Air Mixing Systems and Equipment

Overview

- SCR Fundamentals
- Vapor Injection vs. Aqueous Injection
- Hobbs Power Station
- CFD Inputs & Assumptions
- CFD Results:
    - Baseline and Optimization
    - Addition of Static Mixers
    - Optimization w/Static Mixers
- Conclusions

SCR Fundamentals:



- **Proper proportions of NH3 and NOx are needed**
- **Assumes sufficient depth of a properly functioning catalyst**

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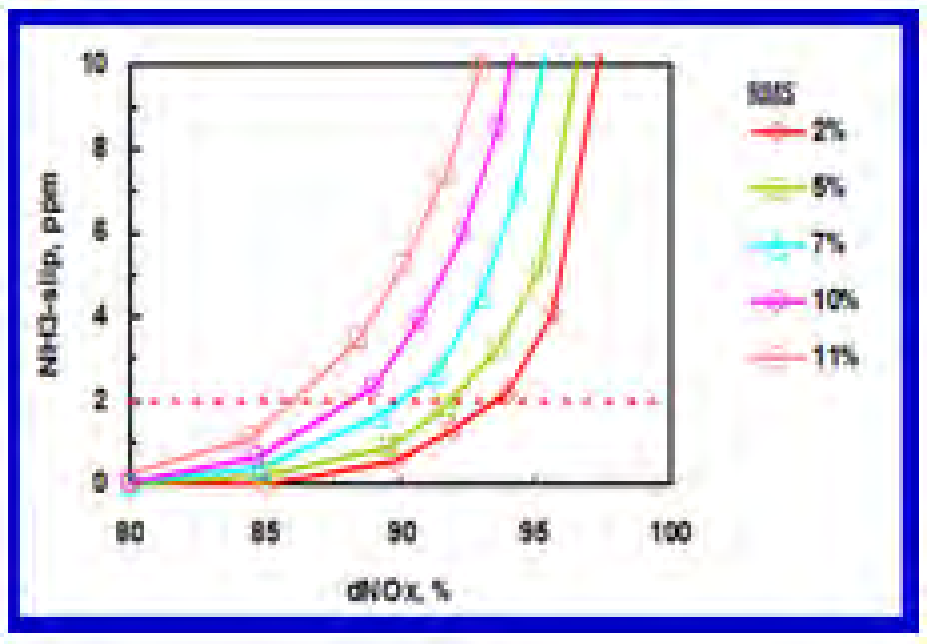
SCR Fundamentals



NH_3/NO ratio < 1 ⇨ N_2, H_2O, and excess NO

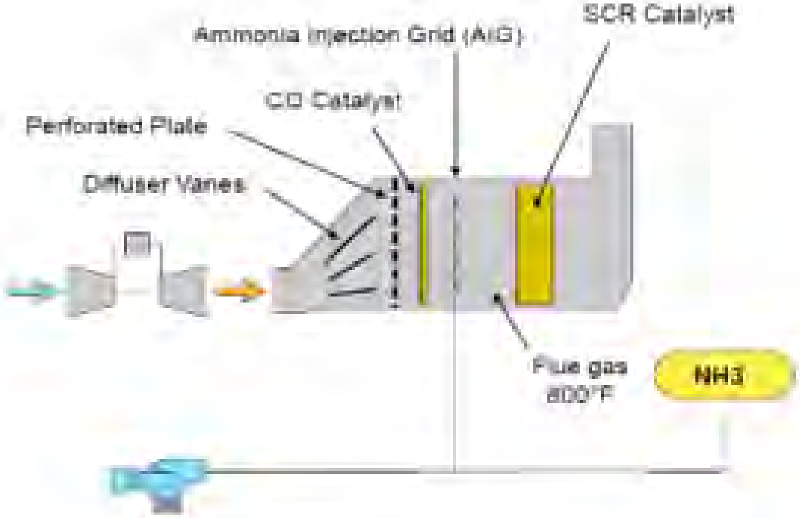
NH_3/NO ratio = 1 ⇨ N_2 and H_2O

NH_3/NO ratio > 1 ⇨ N_2, H_2O, and excess NH_3

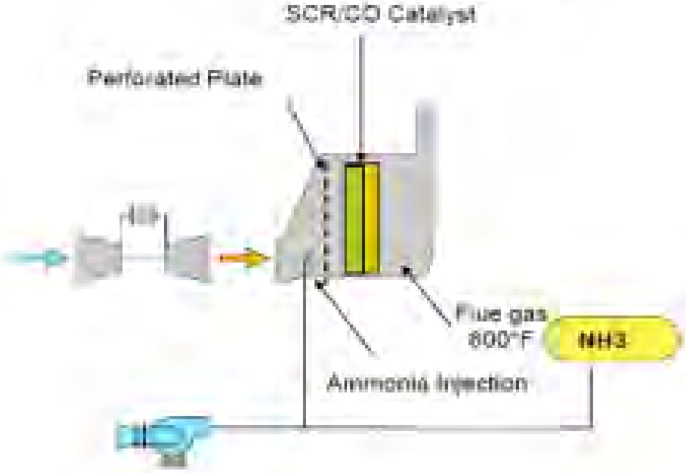
$$RMS = \frac{Standard\ Deviation\ of\ \frac{NH_3}{NO_X}\ ratio}{Mean\ of\ \frac{NH_3}{NO_X}\ ratio}$$

Graphics courtesy of FERCo

Vapor NH_3 Injection vs. Aqueous NH_3 Injection



TRADITIONAL



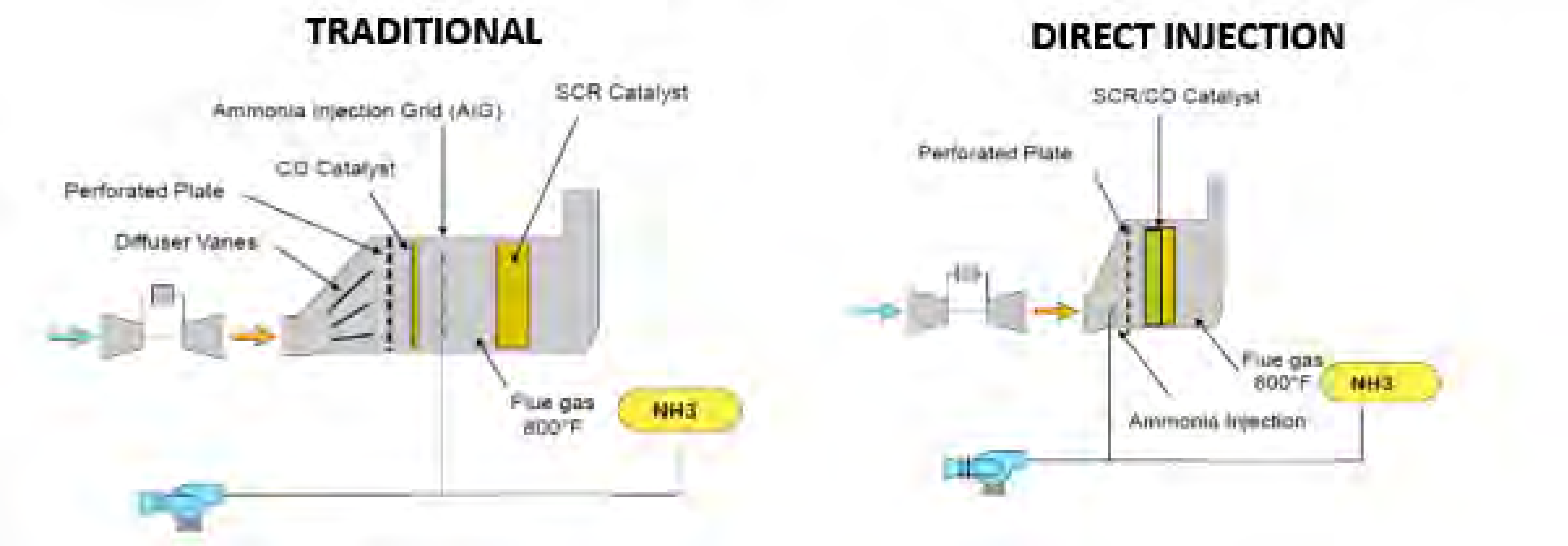
DIRECT INJECTION

- Costly and complex AFCU
  - Unreliable hot gas fans
- Costly and complex AIG
  - Hard to tune
  - Typically NH3:NOx **10% RMS** or higher
- Two layers of catalyst (CO, SCR)
- Overall longer HRSG, footprint

- Simple and reliable AFCU
  - Metering pumps and small compressor station
- Eliminates AIG
  - Simple to tune
  - Achieves NH3:Nox of **5% RMS**
- Single layer of catalyst (CO + SCR)
- Smaller, more compact HRSG, footprint

Graphics courtesy of LP Amina

Vapor NH_3 Injection vs. Aqueous NH_3 Injection


TRADITIONAL

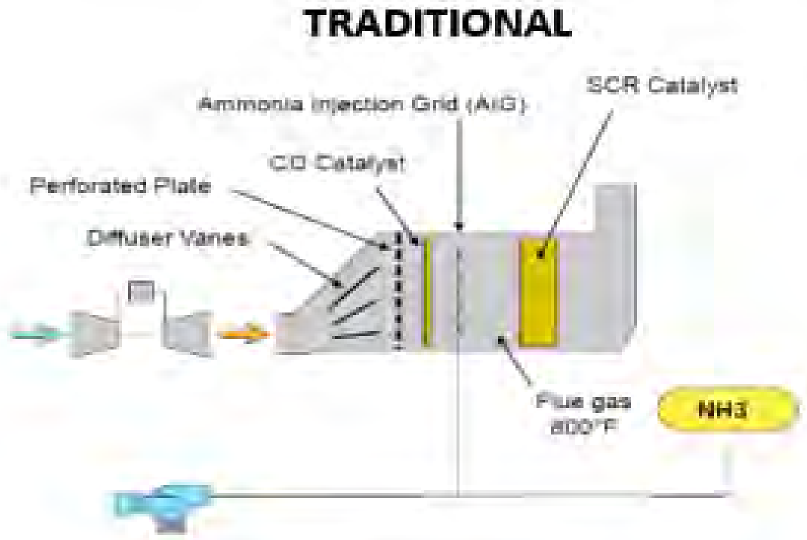
DIRECT INJECTION

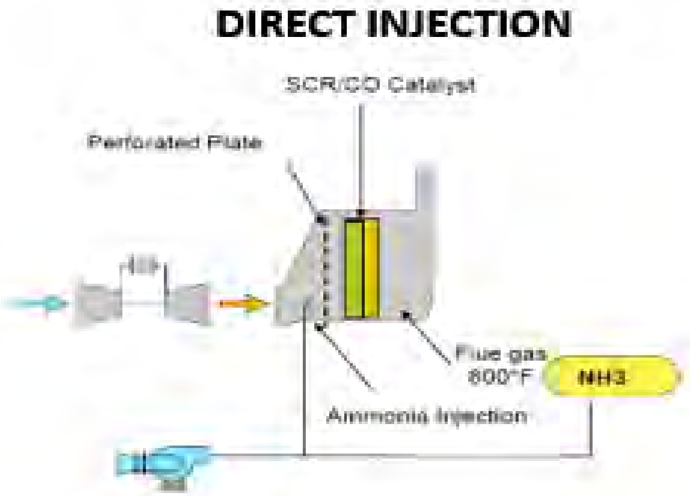
CAPITAL COSTS

Item	Traditional		Direct Injection	
AFCU Skid	$$$	Hot Gas Fans, Vaporizer	$	Pumps
Injection System	$$$	AIG with 2000+ holes	$$	8-12 dual-fluid lances
Interconnect Piping	$$$	Large bore, insulated	$	Small bore, uninsulated

Graphics courtesy of LP Amina

Vapor NH_3 Injection vs. Aqueous NH_3 Injection





OPERATING COSTS

Item	Traditional		Direct Injection (UNFIRED)		Direct Injection (FIRED)	
Ammonia	X	-	X	No change	XX	Negligible due to SNCR Effect
Atomizing Air	Y	Air-atomized vaporizer	Y	No change	Y	No change
Electrical Consumption	ZZZ	Hot gas fans	Z	Pumps	Z_2	Pumps

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Graphics courtesy of LP Amina

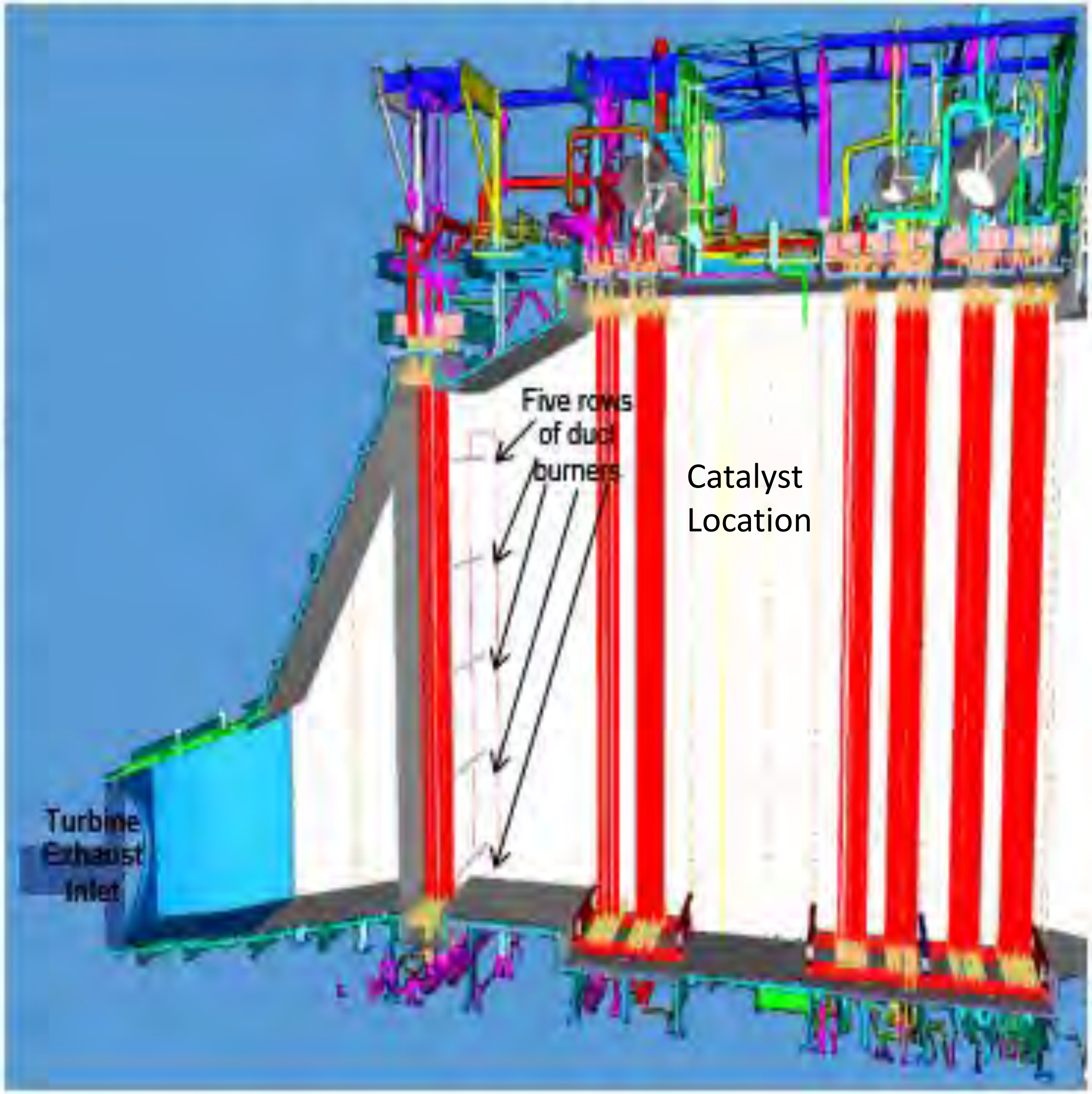
HOBBS POWER STATION MODELING OVERVIEW

2 x 2 x 1 combined cycle power plant built in New Mexico.

Plant relocated by Colorado Energy from Mississippi. Two MHI 701Fs with Aalborg three-pressure HRSG downstream (~550 MW rated, duct burners, NG fuel, with a gas flow rate of ~3,500,000 lbm/hr).

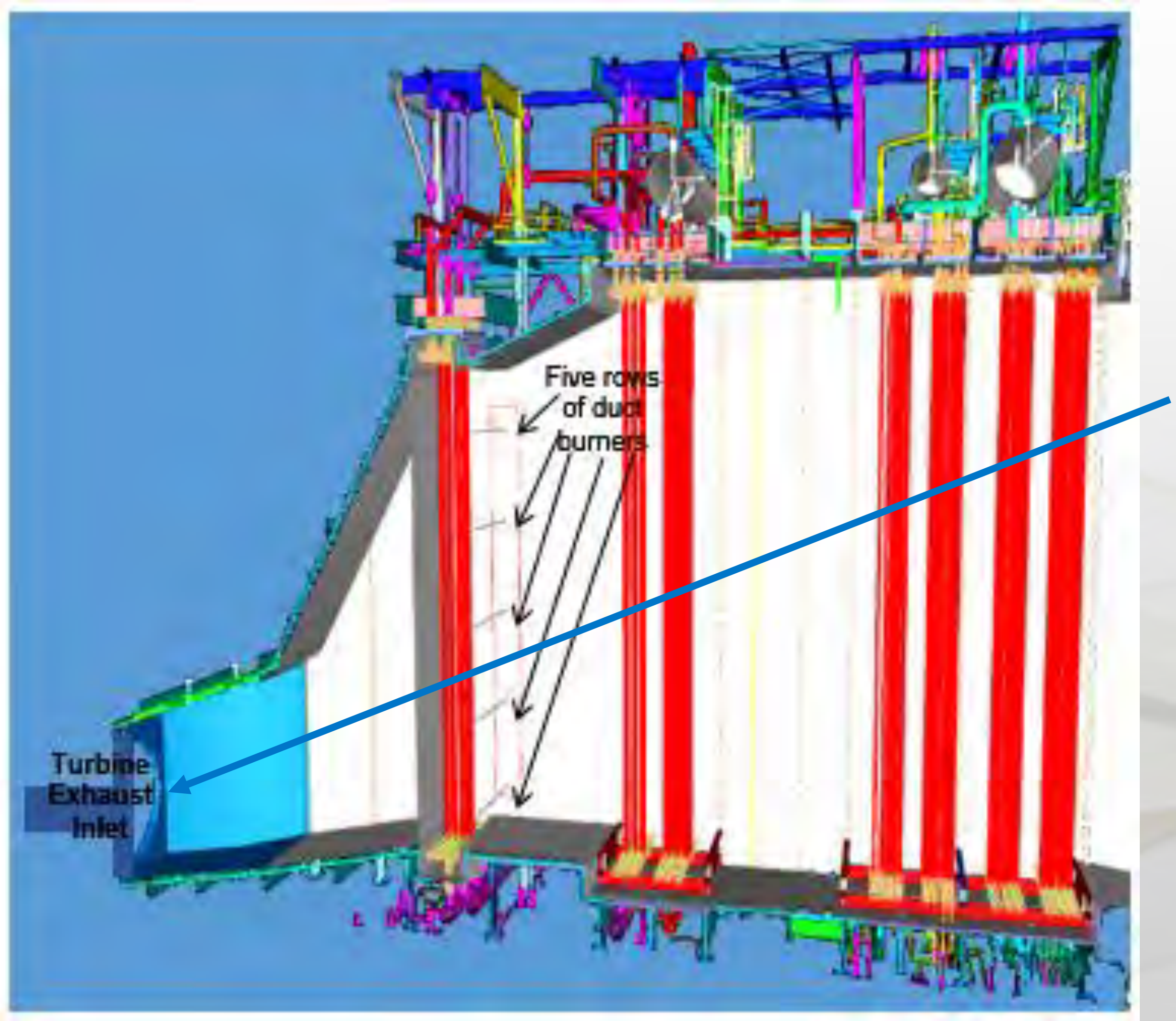
Contains both CO and SCR catalyst, as well as traditional AIG.

Will need to improve emissions reduction to comply with EPA standards.



Graphics courtesy of LP Amina

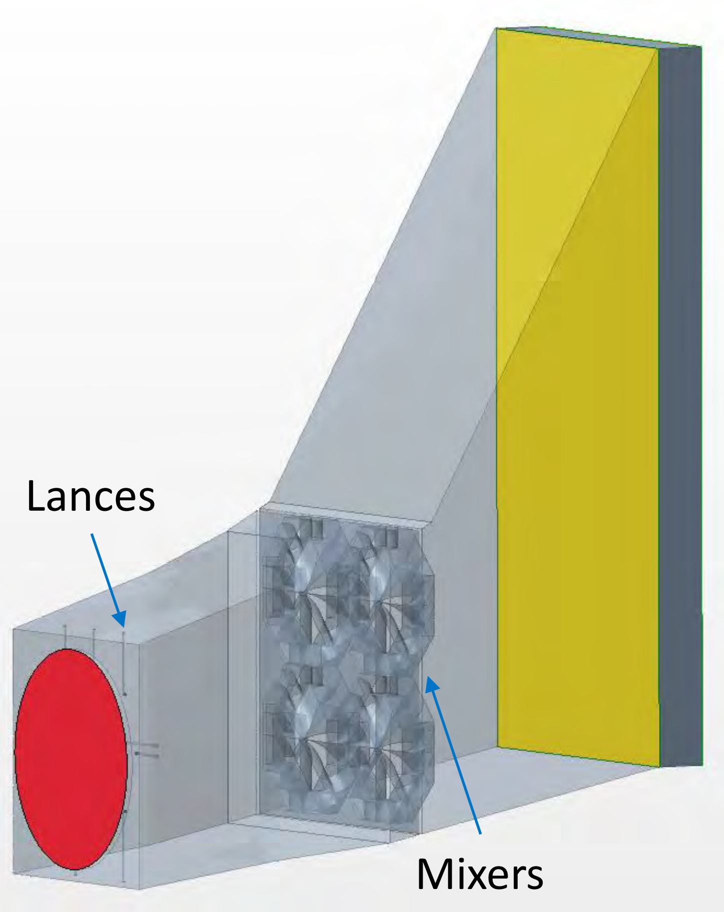
Hobbs Power Station



Worse case scenario Center line of turbine exit duct nearly even with bottom of heat exchangers/catalyst bed

Graphics courtesy of LP Amina

Objectives of Case Study:

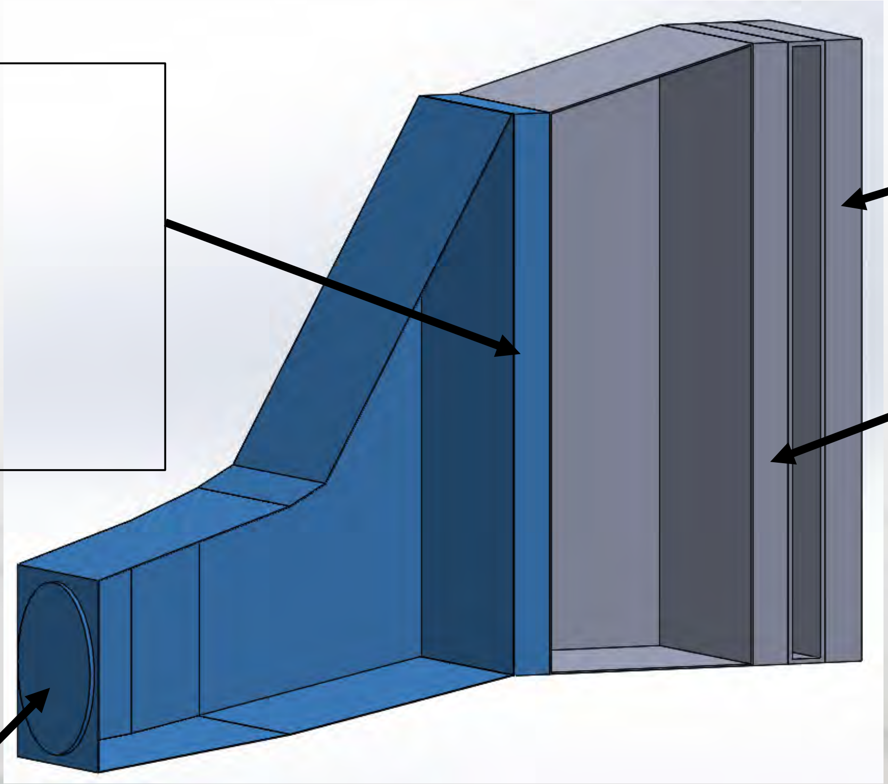


- **Determine if lances and mixers can be optimized to get lowest possible RMS**
- **Focus on mixing performance (low RMS) and pressure drop (minimize)**
- **Some aspects of mixer and lance construction, installation, and survivability considered but are not the focus of study**

CFD Model Inputs & Assumptions:

- Model domain from GT exit to duct burners
- Inlet
    - Velocity profile
    - Temperature and NOx concentration assumed constant
        - Could be variable if desired/known
- 4.8M cells with mixers and lances
    - Mesh refinement around inlet, lances, and mixers
    - Solution time 6-8 hours
- Porous region used to model the secondary superheater and reheater, and the duct burners
    - Approximately 700 Pa (2.8 in wc) pressure drop
    - 1.22 m thick
- Turbulent, steady state model
- Not yet validated against experimental/field data

Model domain



- Secondary Superheater
- Secondary Reheater
- Duct Burner

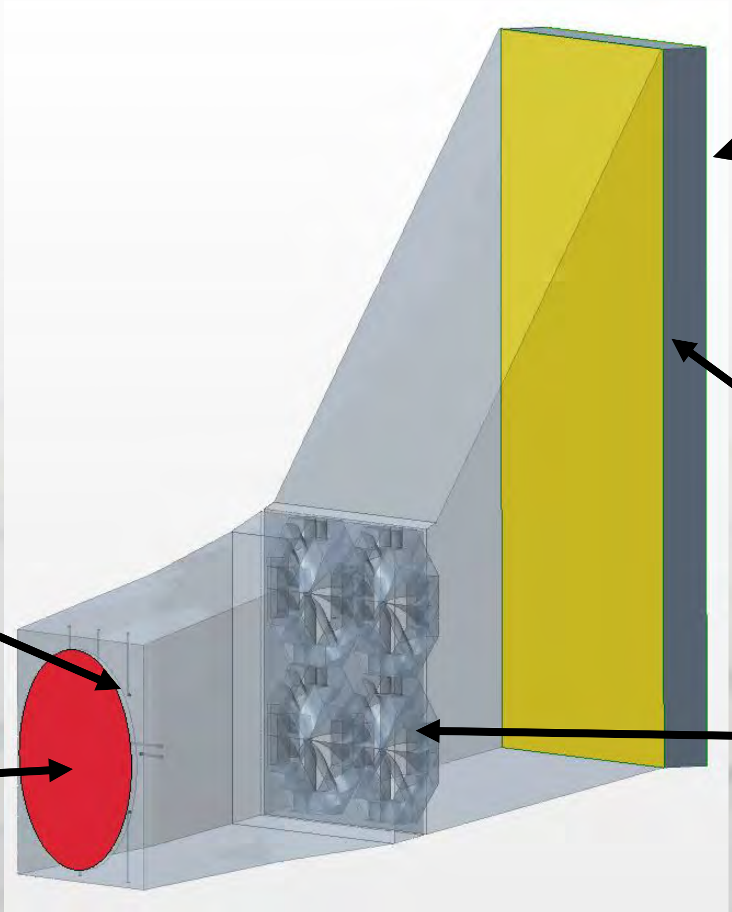
Catalyst

Primary Superheater

Turbine outlet

CFD model only includes region shown in blue

Model geometry and boundary conditions



Injectors
- Bodies
- Inlet for assist air
- Droplet source

Inlet

Outlet

Porous region (heat exchangers and duct burners)

Mixers (if applicable)

Droplets

- **Multicomponent droplet evaporation model of 19% aqueous ammonia**
- **Droplet size modeled with a Rossin-Ramler distribution**
  - **D32 = 19 µm**
  - **Dv0.9 = 47 µm**
  - **Dv0.99 = 80 µm**
  - **Particle size distribution taken from data provided by nozzle manufacturer**
- **Injector gas velocities determined from nozzle pressure, flow rate, and orifice size**
- **Most droplet parameters have minimal impact on distribution**
  - **Very rapid droplet evaporation**
  - **NH_3 evaporates out of droplet first**

Optimization method for increased sim eff:

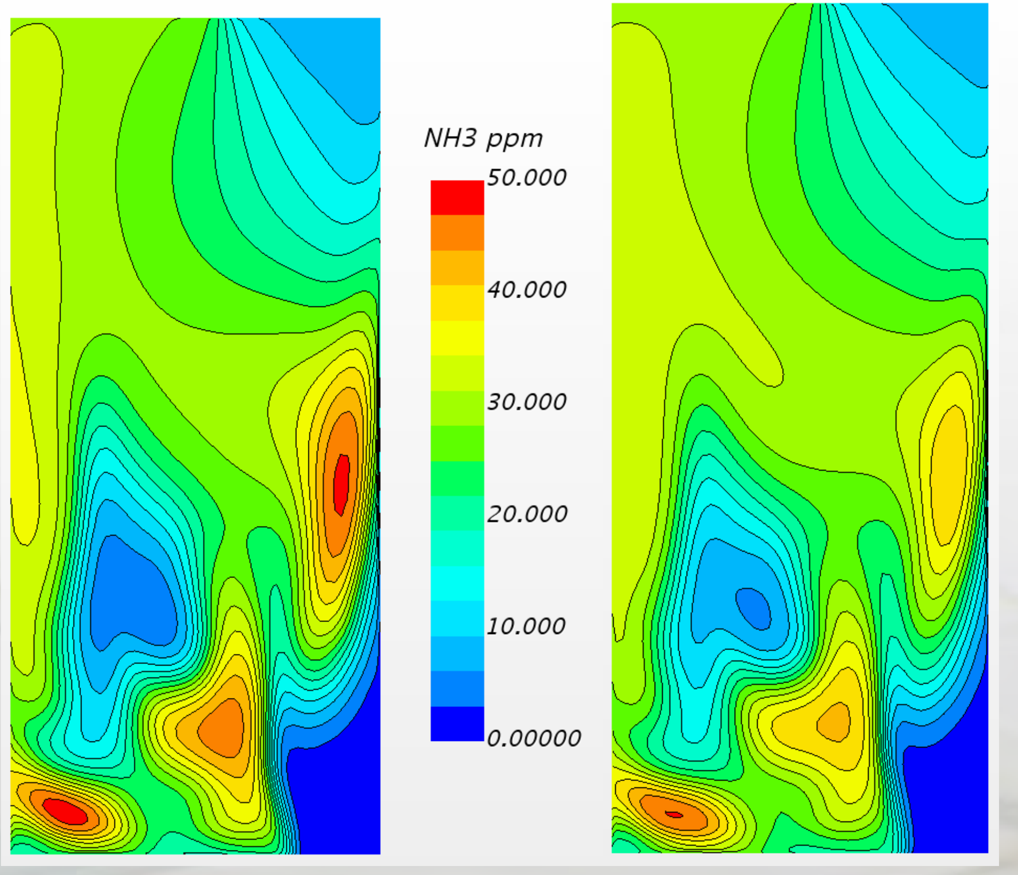
- **Temporarily remove physical lances from model**
  - **Droplets still injected (spray angle and velocity still modeled)**
  - **No assist air**
  - **No flow around lance**
  - **Significantly decreases computation time**
    - **Decreases number of mesh cells**
    - **Eliminates the need to remesh**

- **Trace back low/high regions using backward forecasting of stream lines**
  - **Very useful in situations with complex flow (swirl, backflow, etc.)**

Optimization method

- **Move, add, subtract, and/or change flow rate of injectors**
- **Repeat streamline trace back until point of greatly diminished returns**
- **Add lances back into model and check that solution is not significantly altered**
- **This method reduces CPU time by 4-5x**

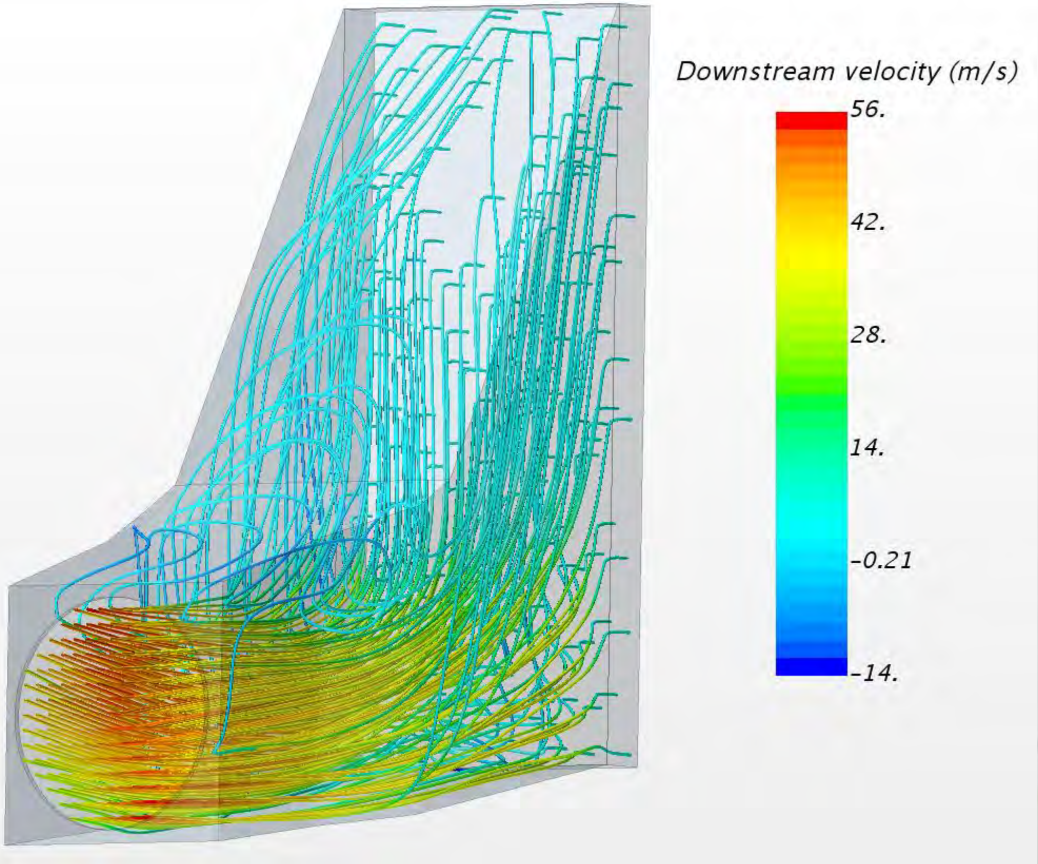
Old with and without lance bodies



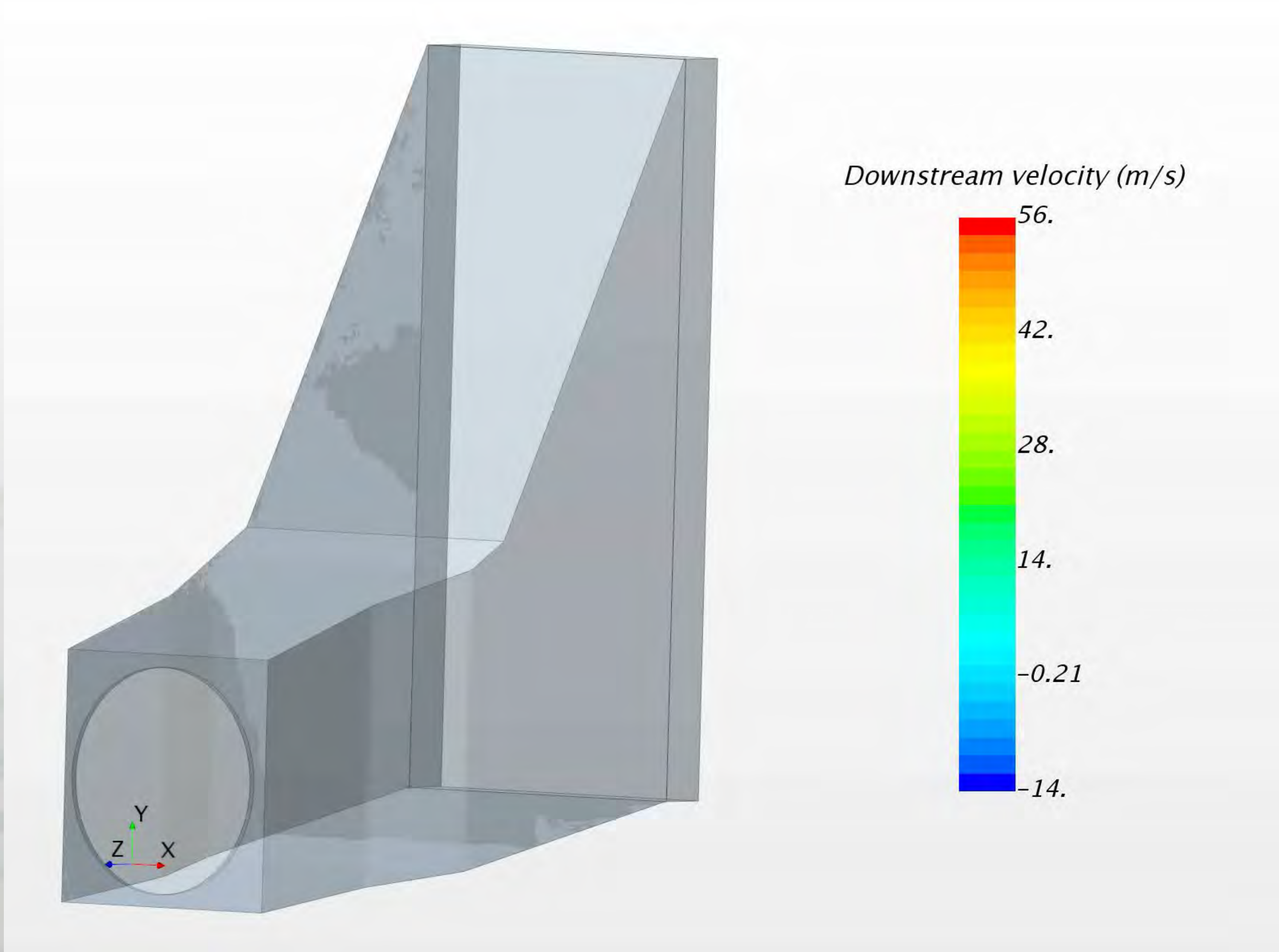
Lances modeled
RMS=43%

No Lances
RMS=38%

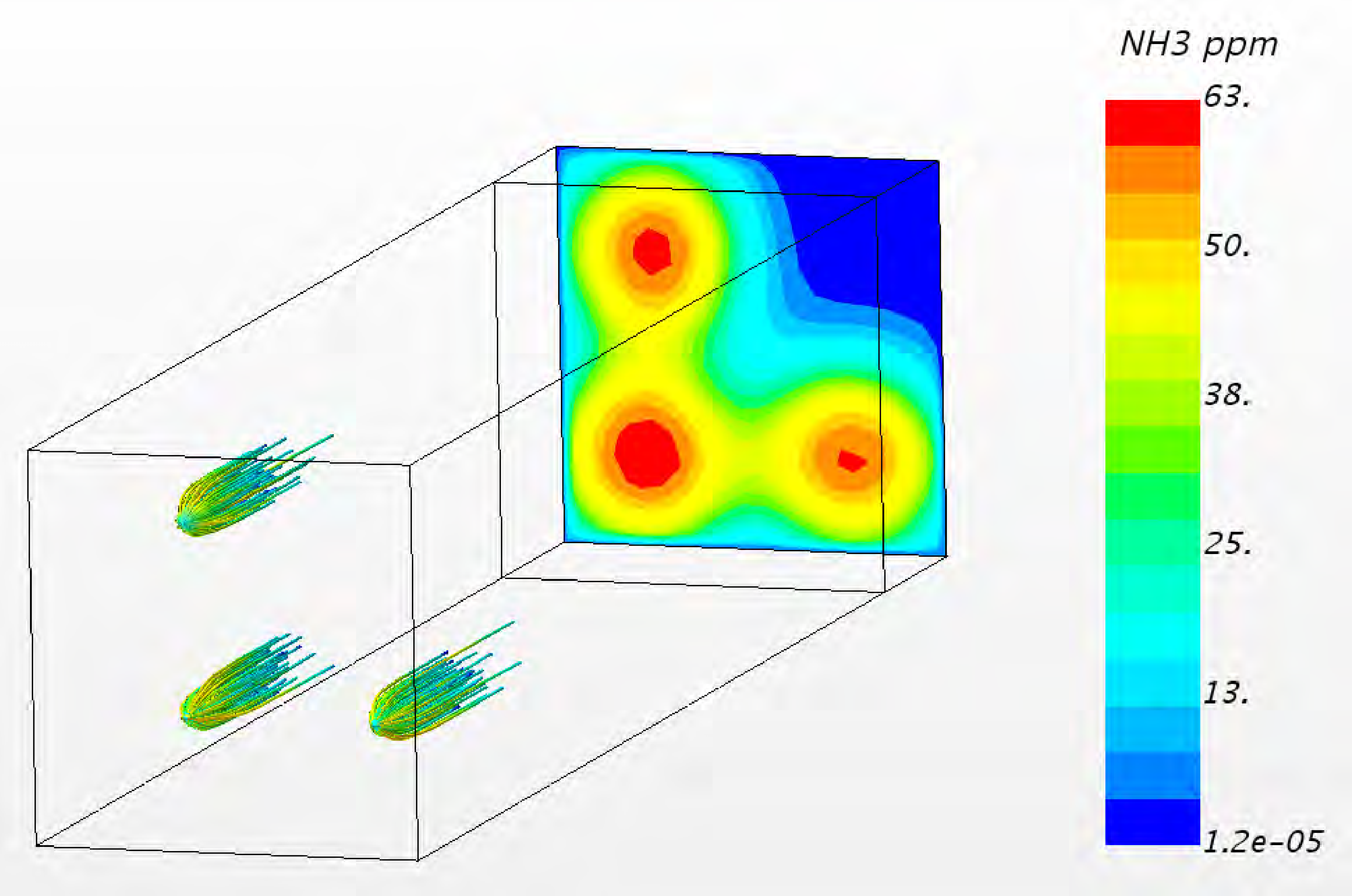
Streamlines are typically projected from the model inlet



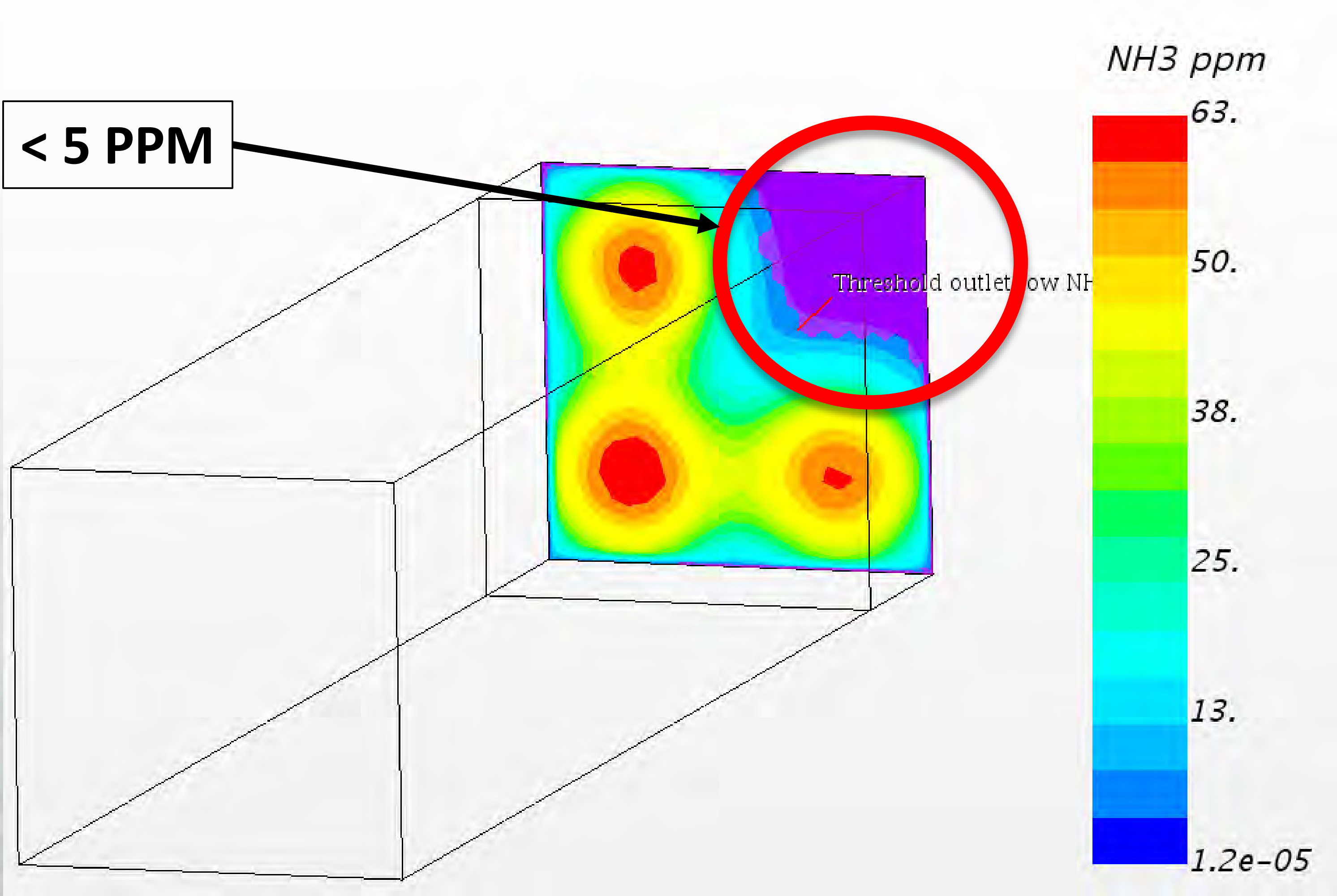
Streamlines are typically projected from the model inlet



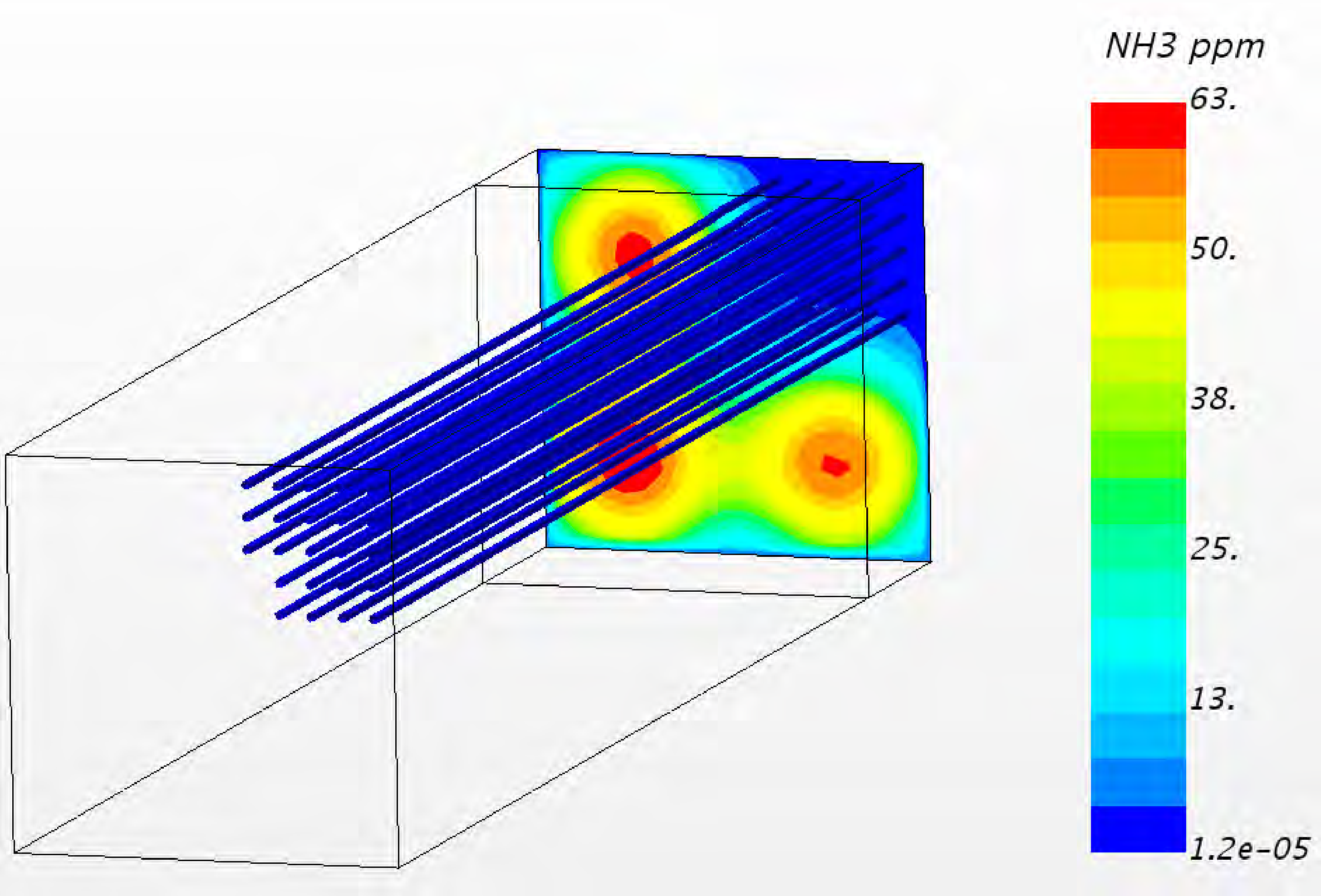
Basic duct, stream line trace back



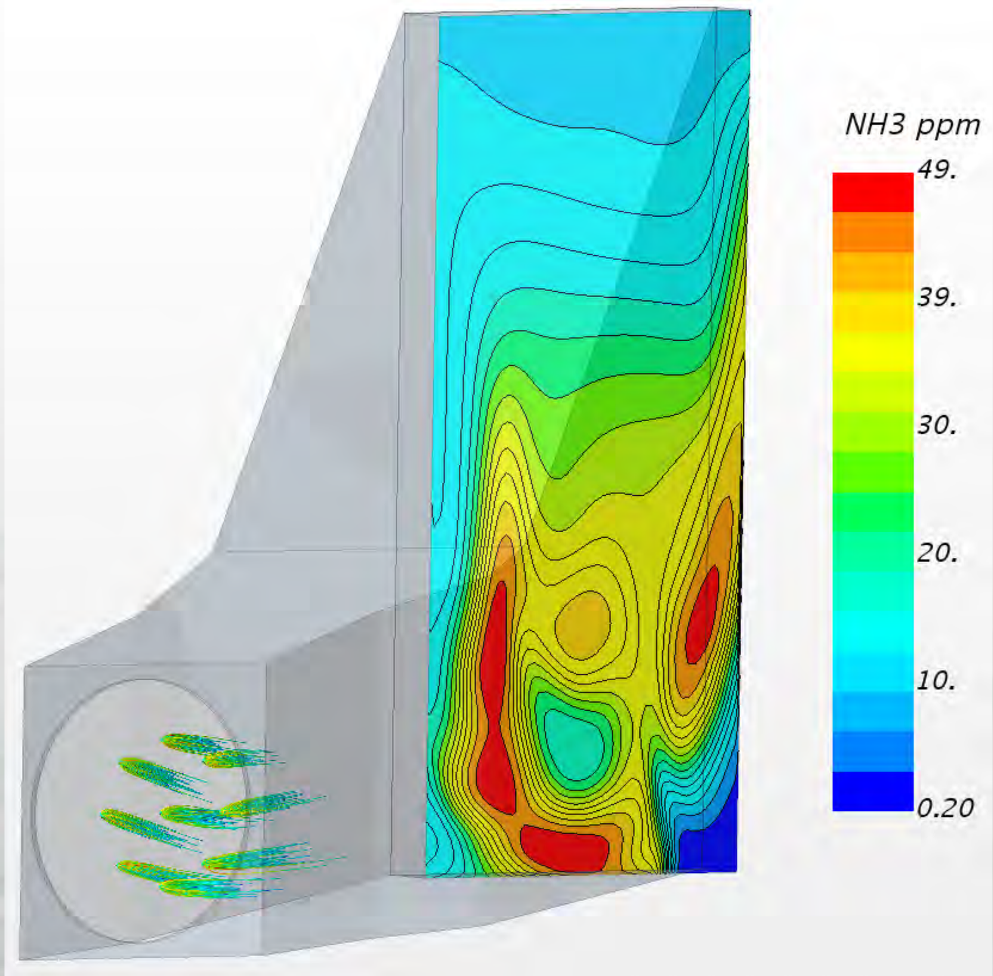
Basic duct, stream line trace back



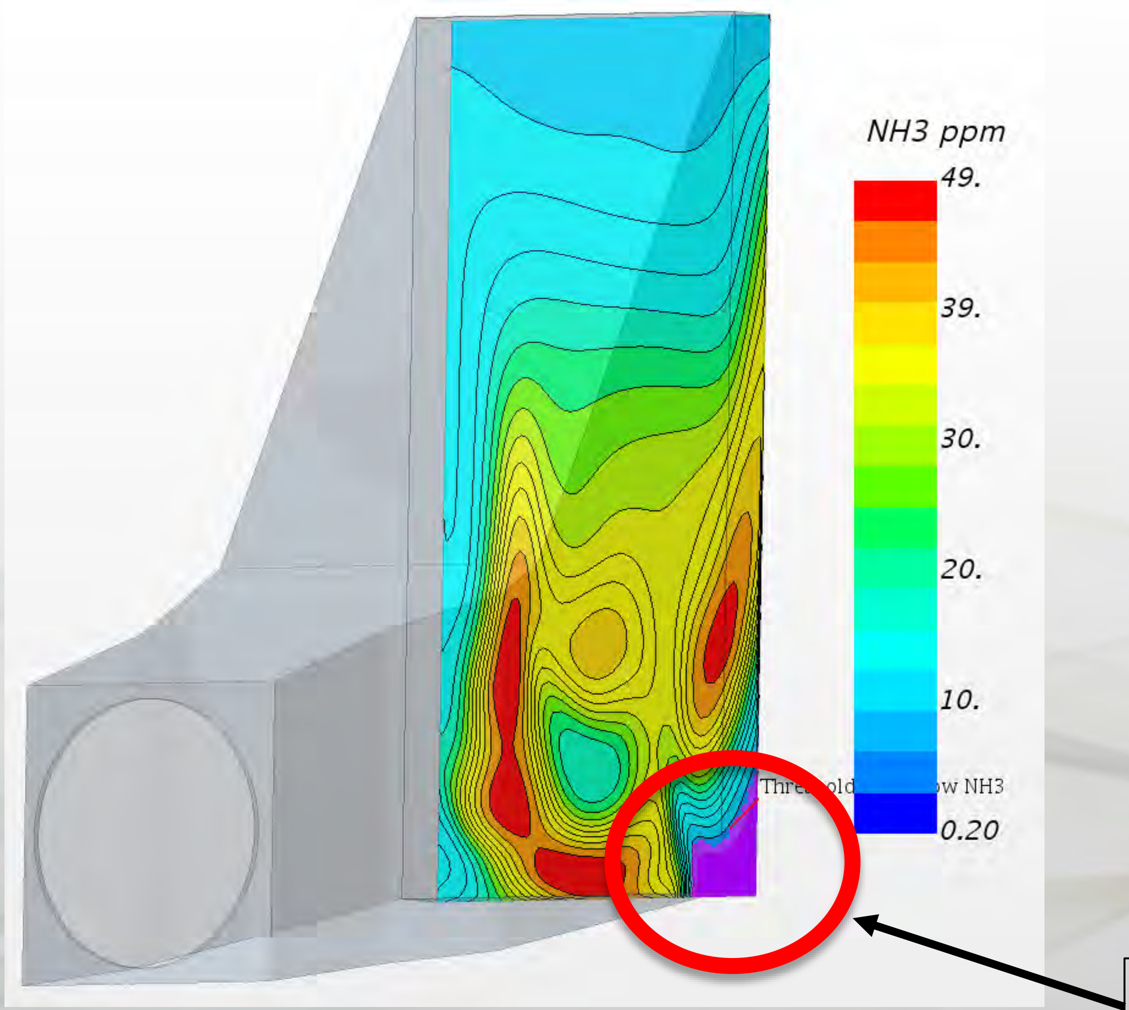
Basic duct, stream line trace back



GT exhaust example, stream line trace back

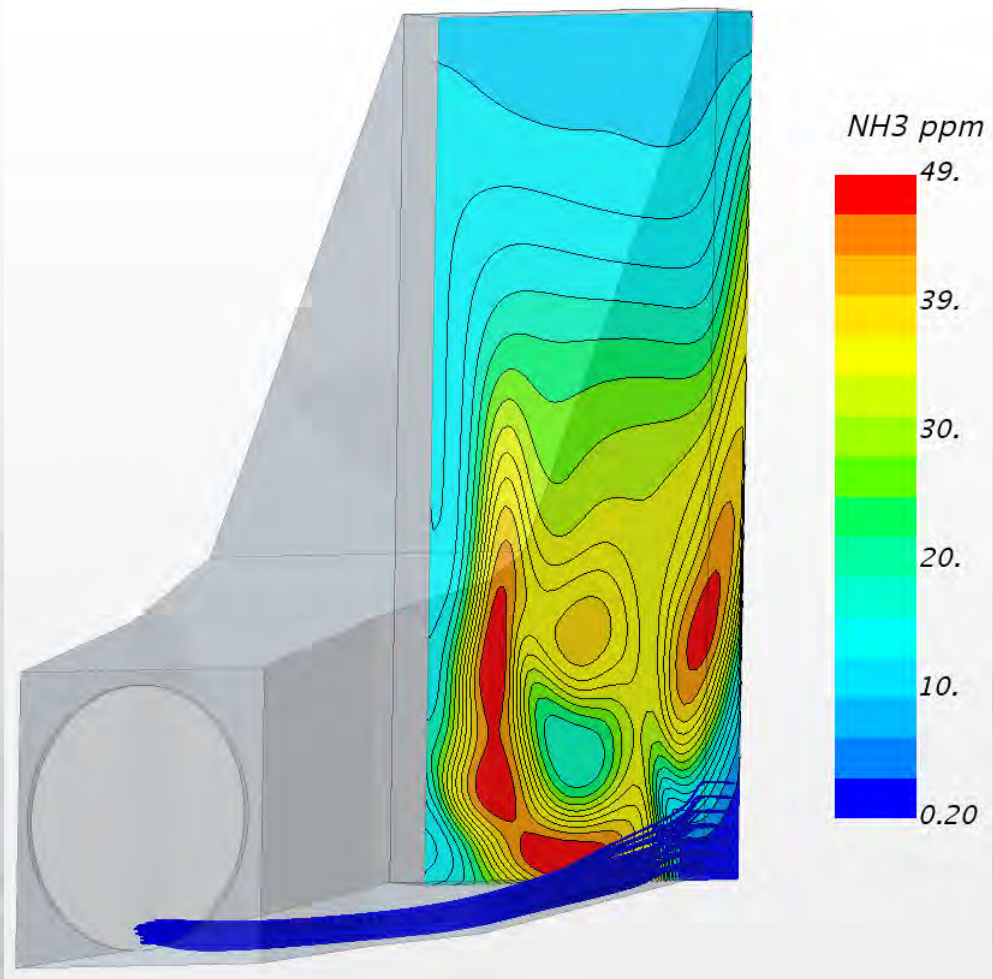


GT exhaust example, stream line trace back

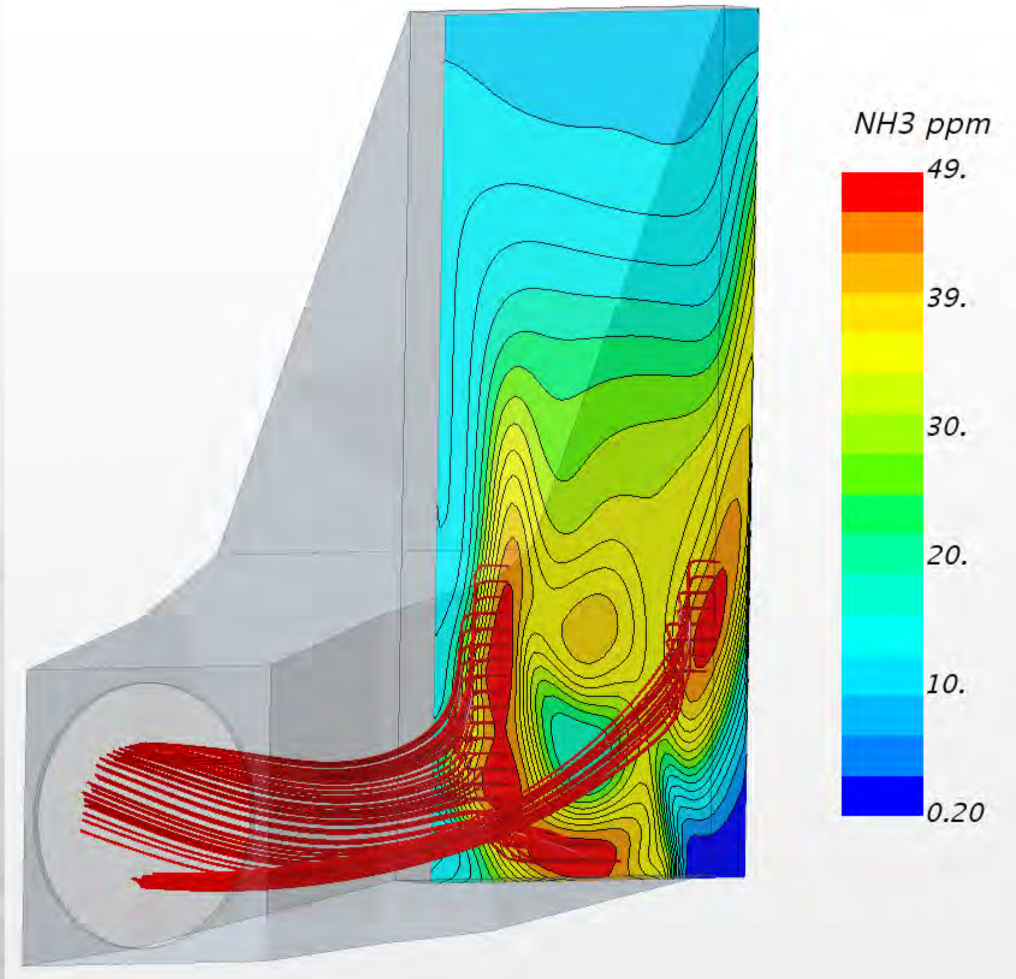


< 5 PPM

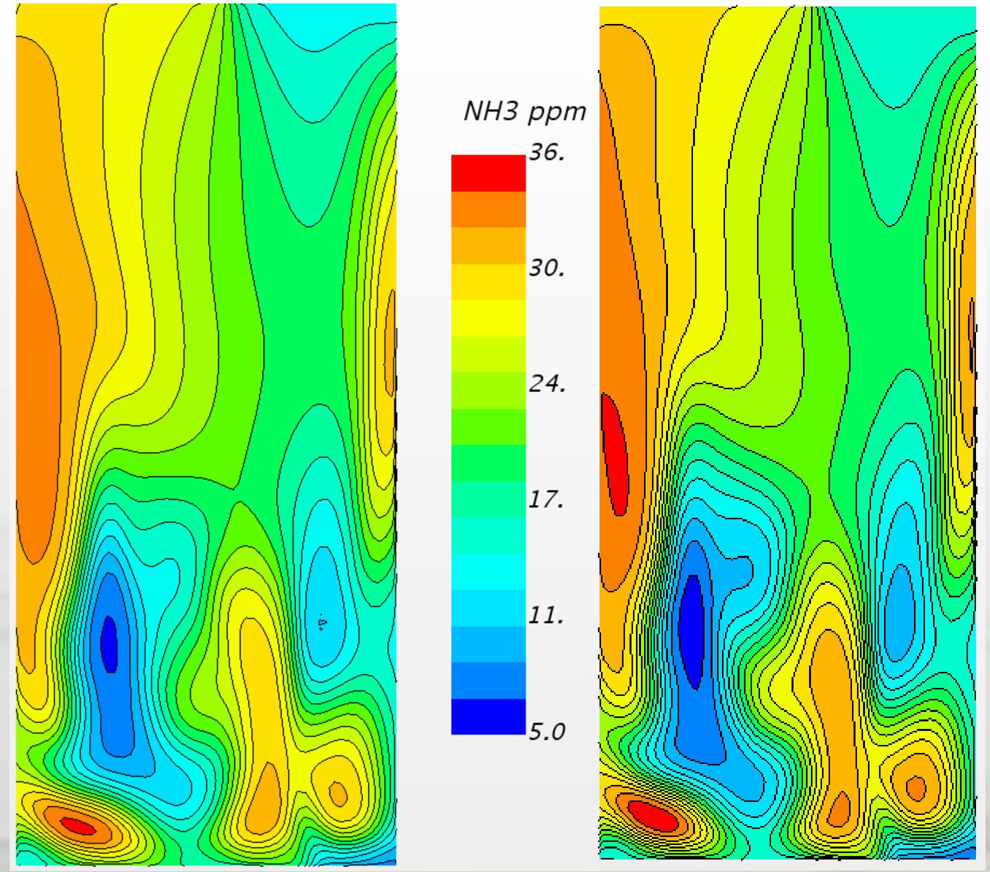
GT exhaust example, stream line trace back



GT exhaust example, stream line trace back



Final case with and without lance bodies, no mixers

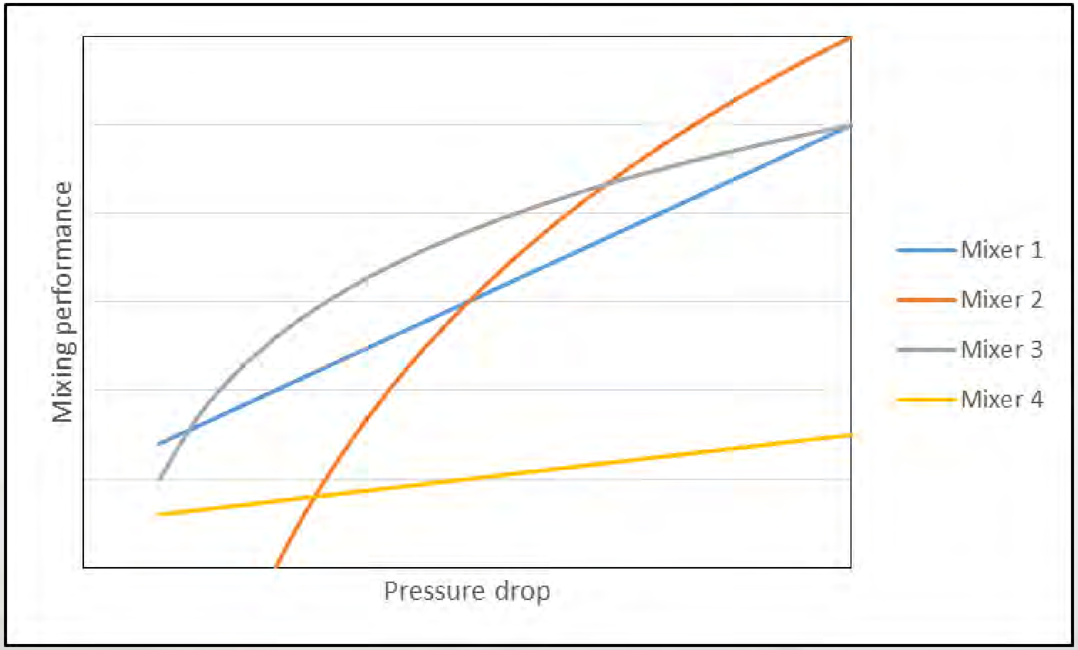


No lance bodies
RMS = 28%

With Lance bodies
RMS = 30%

Addition of mixers

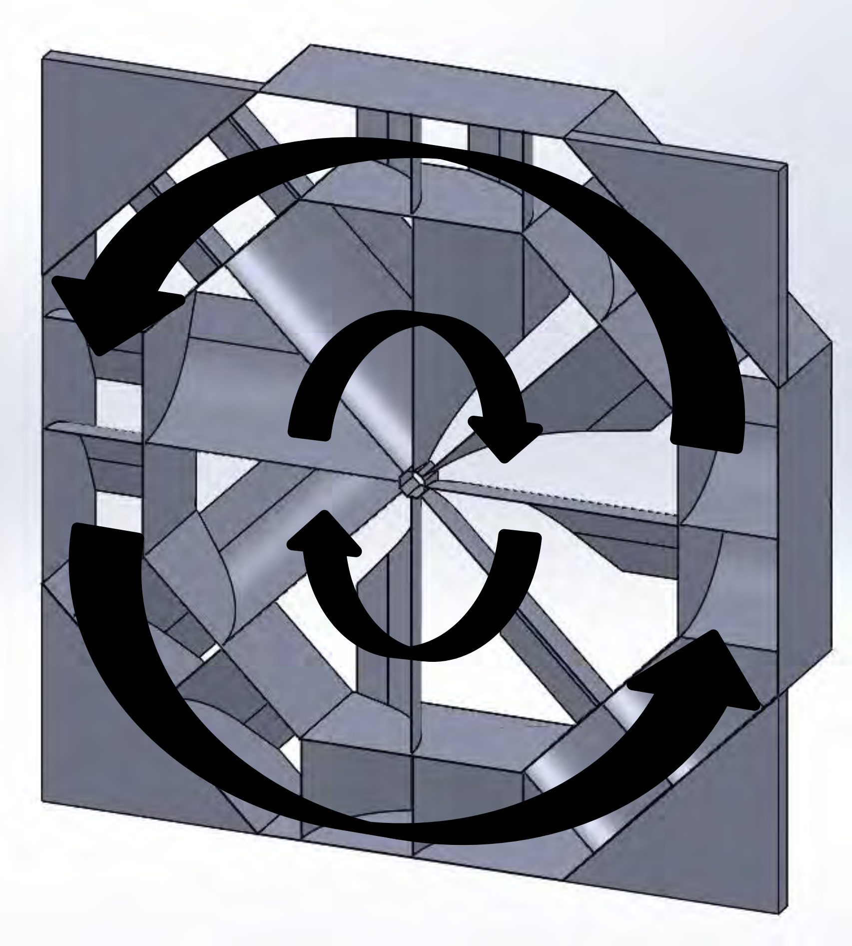
- Types of mixers
  - Rotational
  - Vortex
  - Combination



- Different mixer styles have different trades offs between pressure drop and mixing performance
  - Each style will have a different method of tuning mixers
    - Mixer size
    - Number of mixers
    - Aggressiveness of mixers

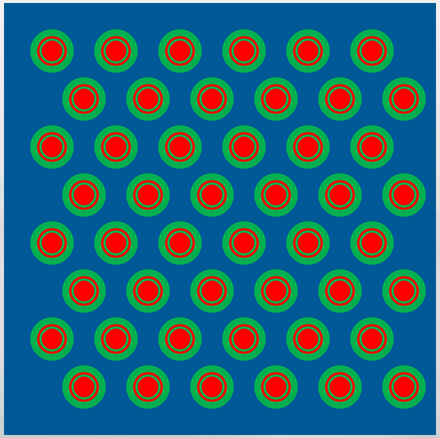
Addition of mixers

- Counter rotational design
  - Mixes using both swirl and vortex
- Mixer trade offs
  - Blade angle
    - Pressure drop vs mixing performance
  - Size
    - Smaller mixers need less downstream distance
    - Easier installation
    - Requires specific conditions to not increase pressure drop



Mixer arrays

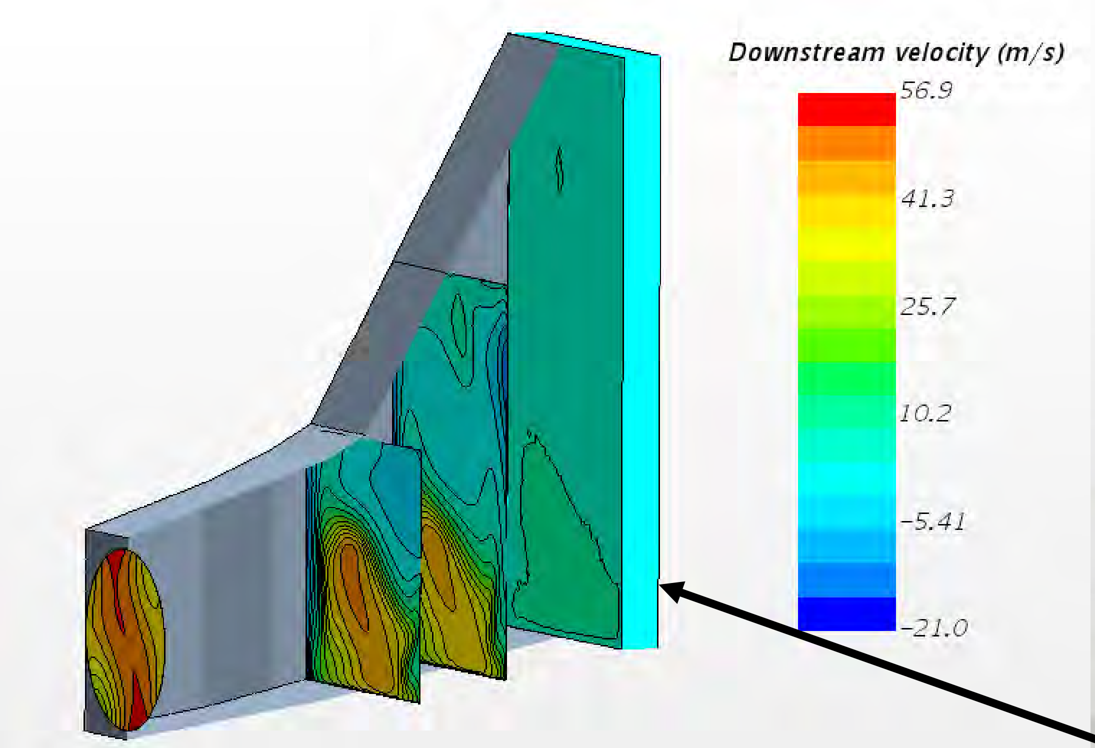
Useful in situations where the stratification pattern is local rather than global



Yes

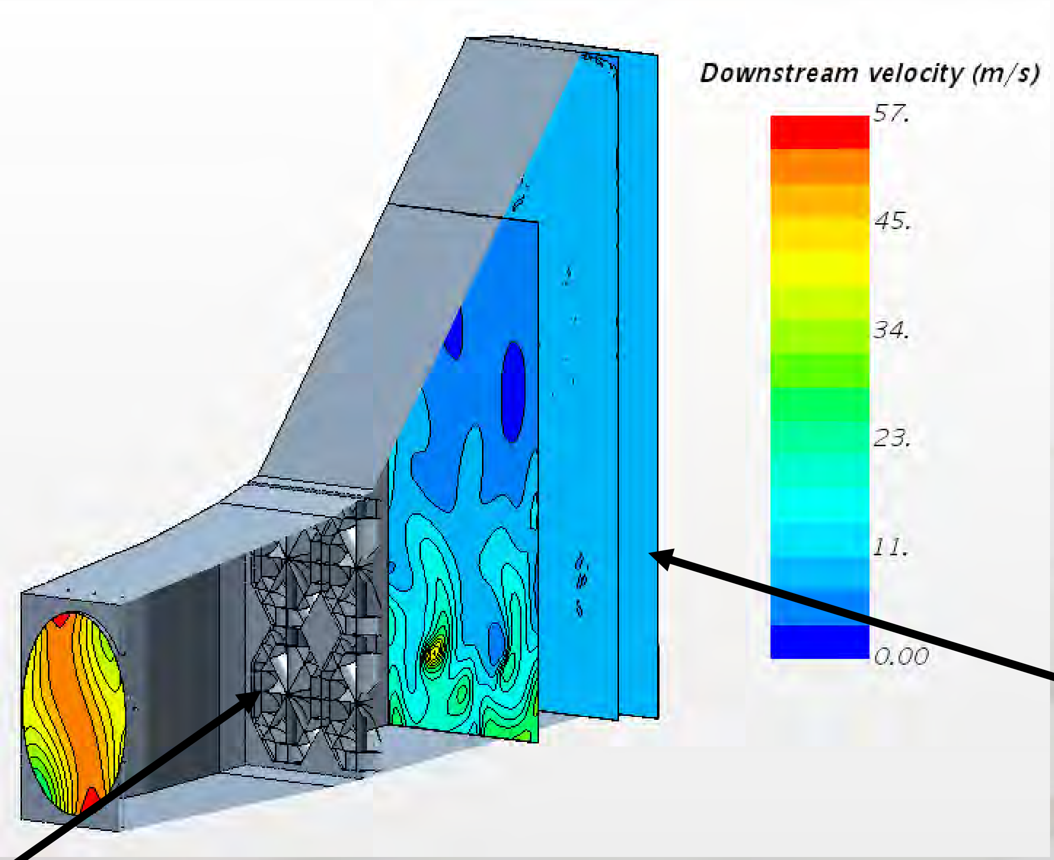
No

Velocity profile without mixers



Velocity RMS at outlet = 14%

Velocity profile with 2x2 array of mixers

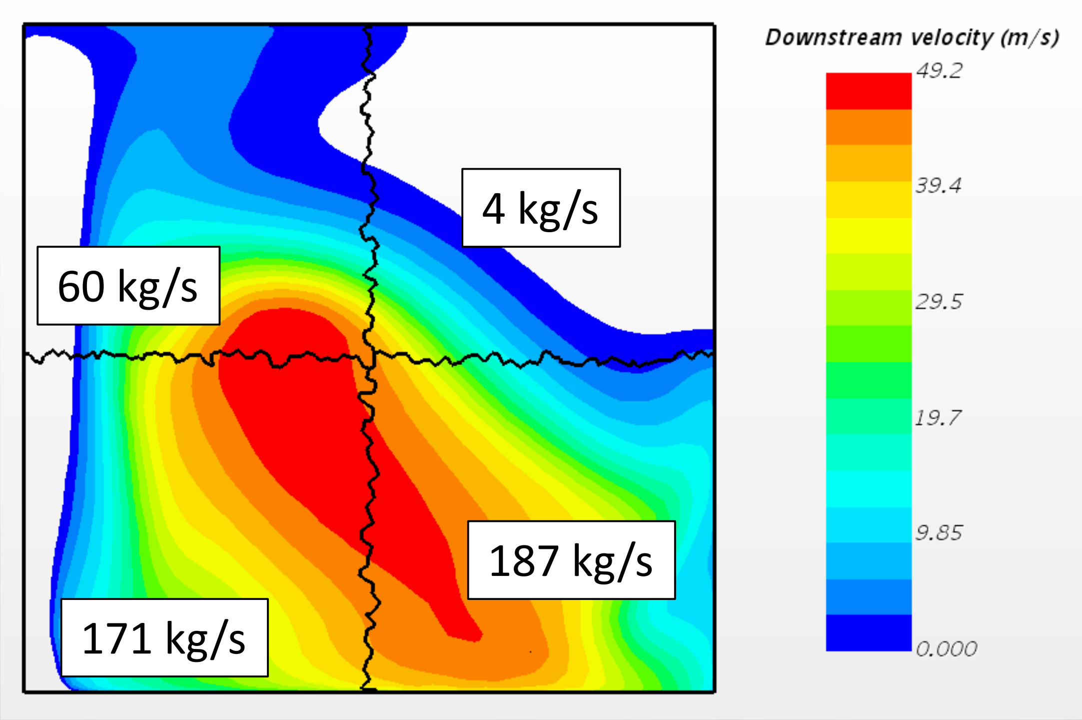


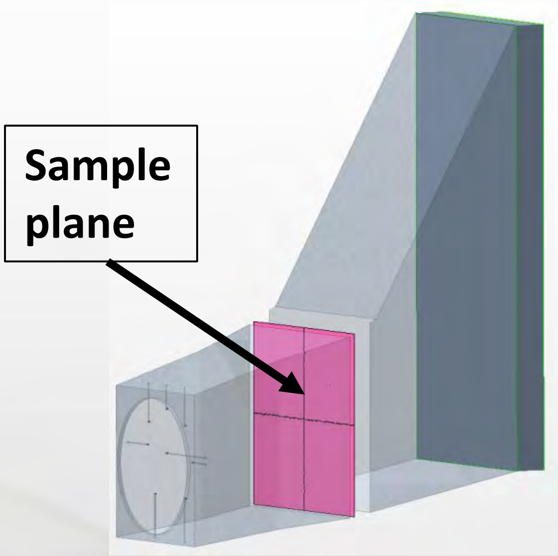
Velocity RMS at outlet = 7%

Mixers

MixerΔP ≈ 1.00” wc

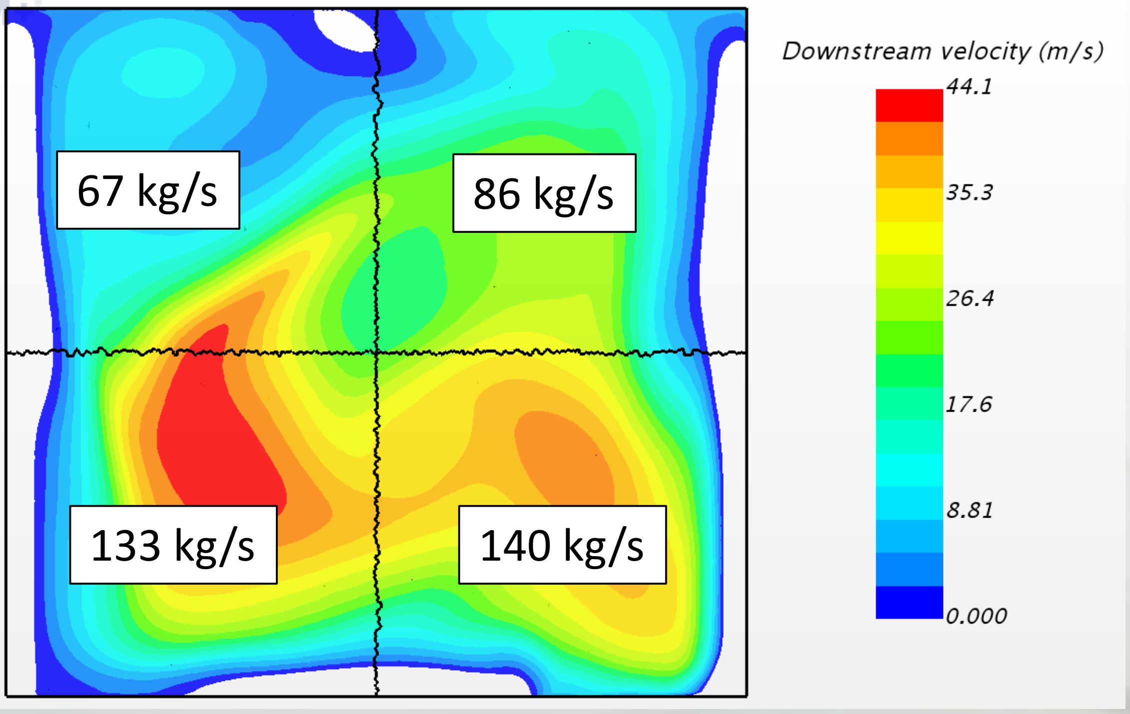
Results from baseline velocity profile

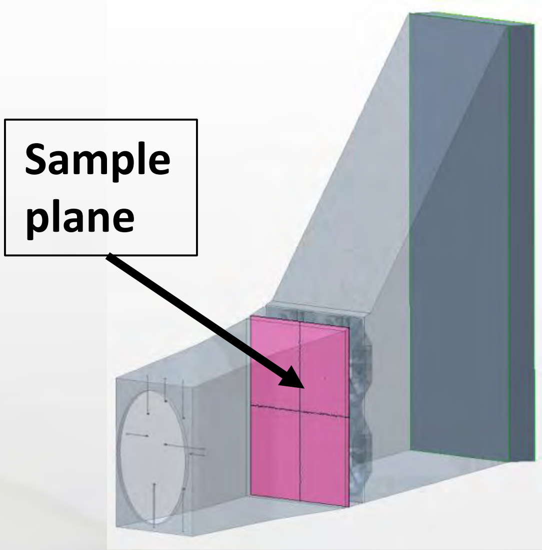




- White areas are regions of negative velocity (recirculations)
- Major mass-flow uniformity issues
- Altering inlet velocity profile results in different but still highly non-uniform mass flow

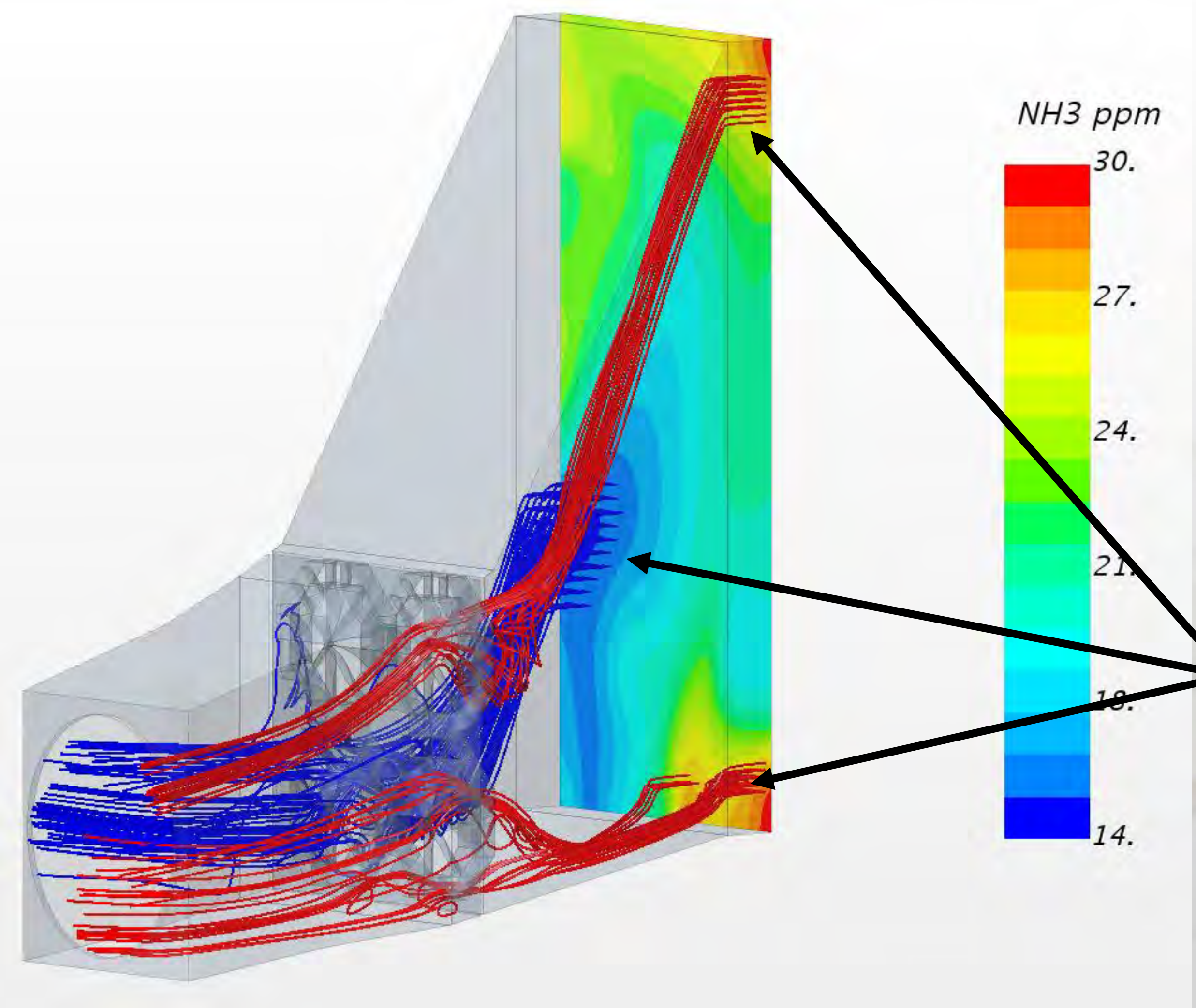
Mixers significantly reduce variation in velocity profile





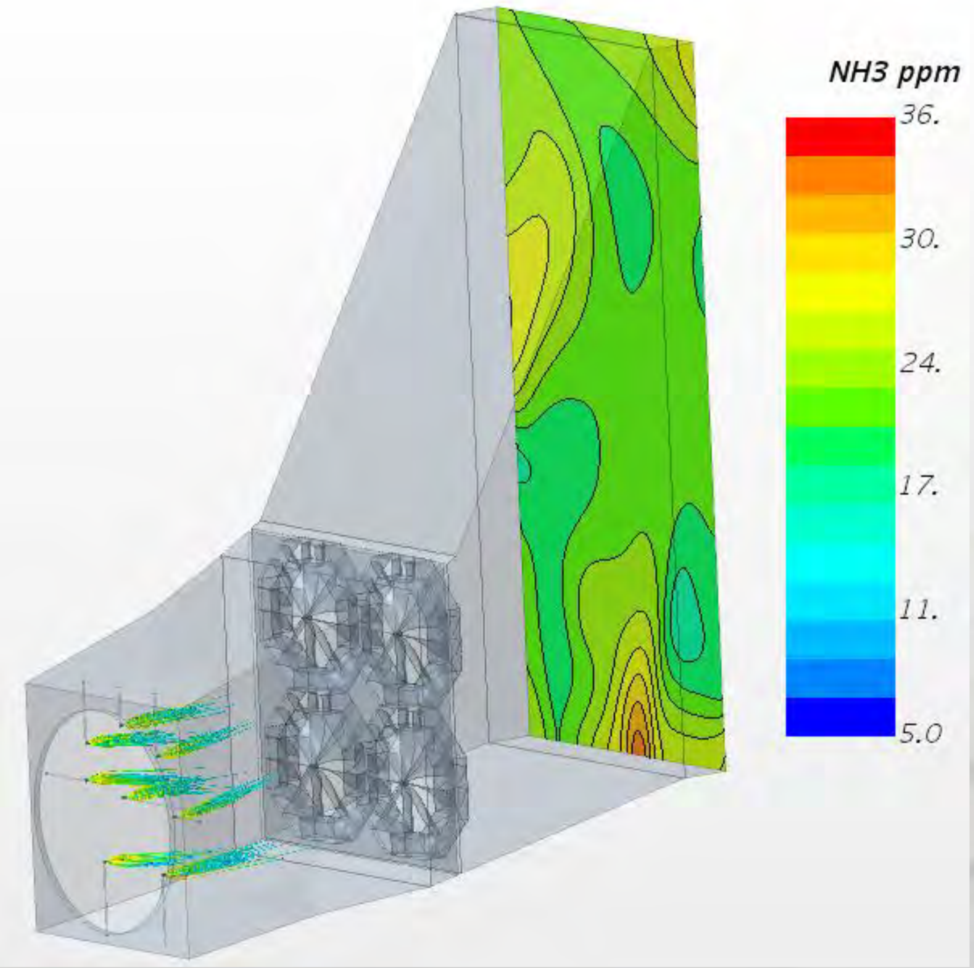
- **White areas are regions of negative velocity (recirculations)**

Optimization 2x2 array of larger mixers

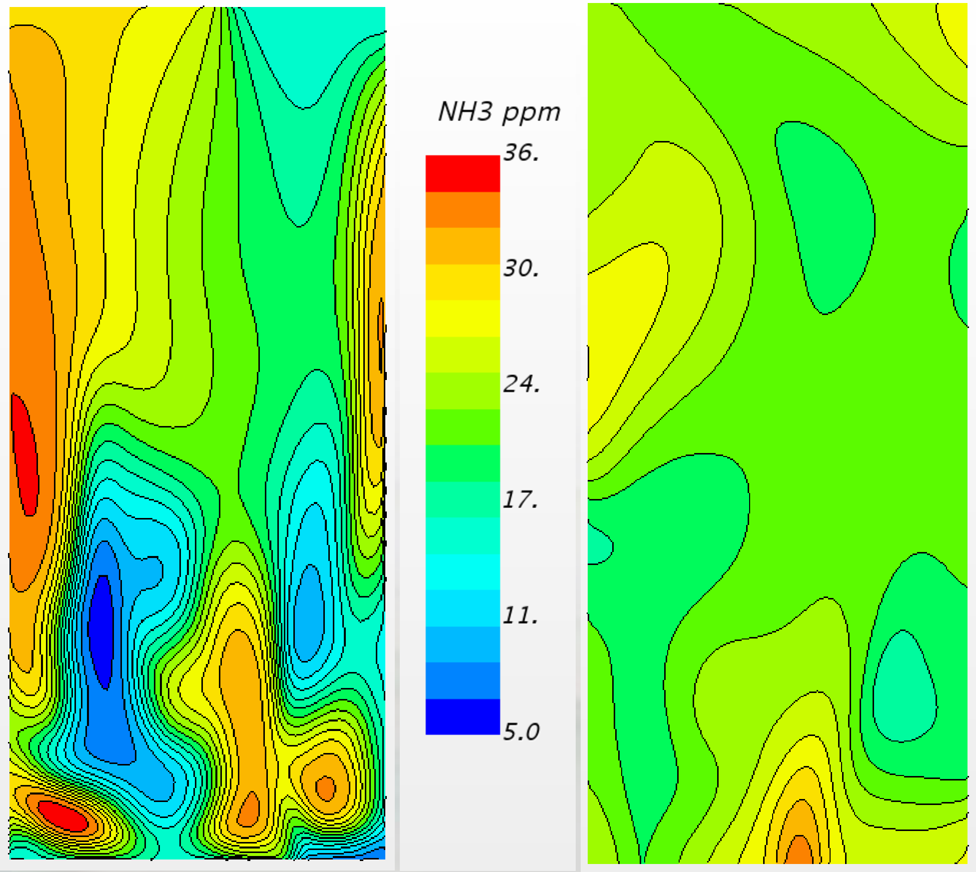


Trace back High and Low regions

Optimization 2x2 array of larger mixers



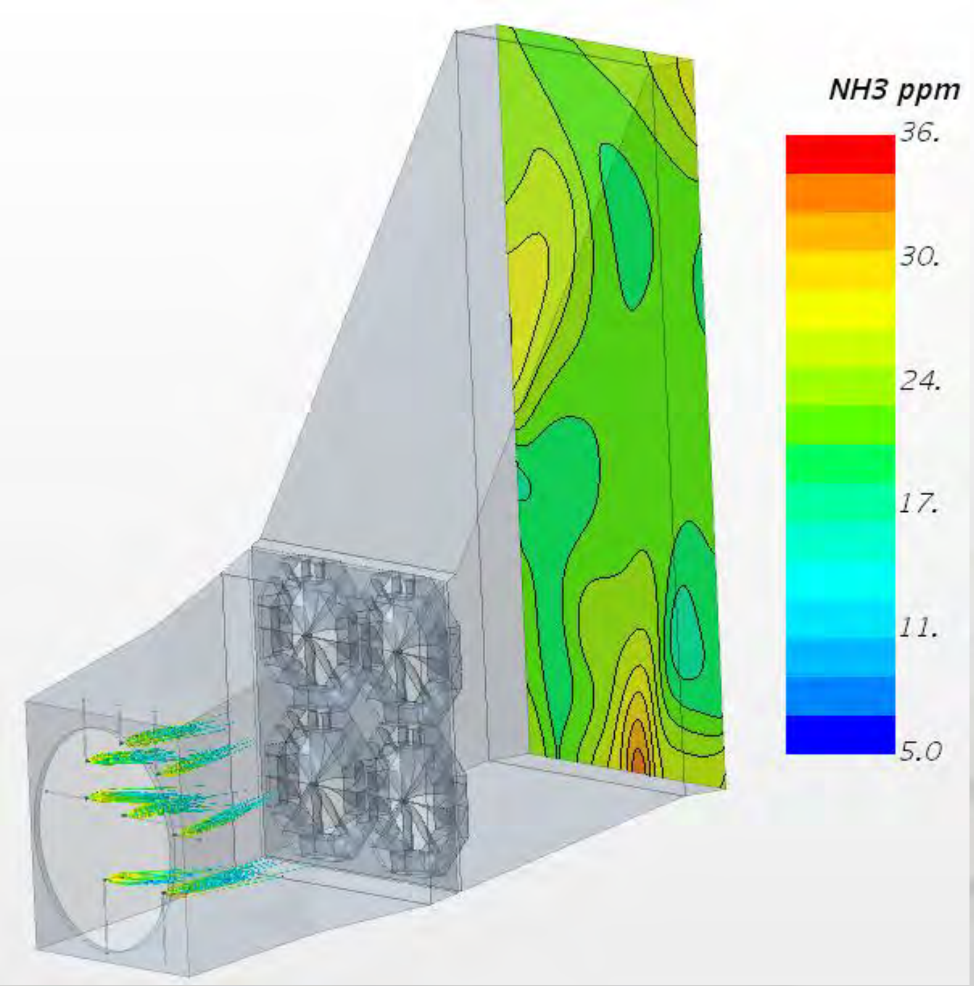
No vs with mixers



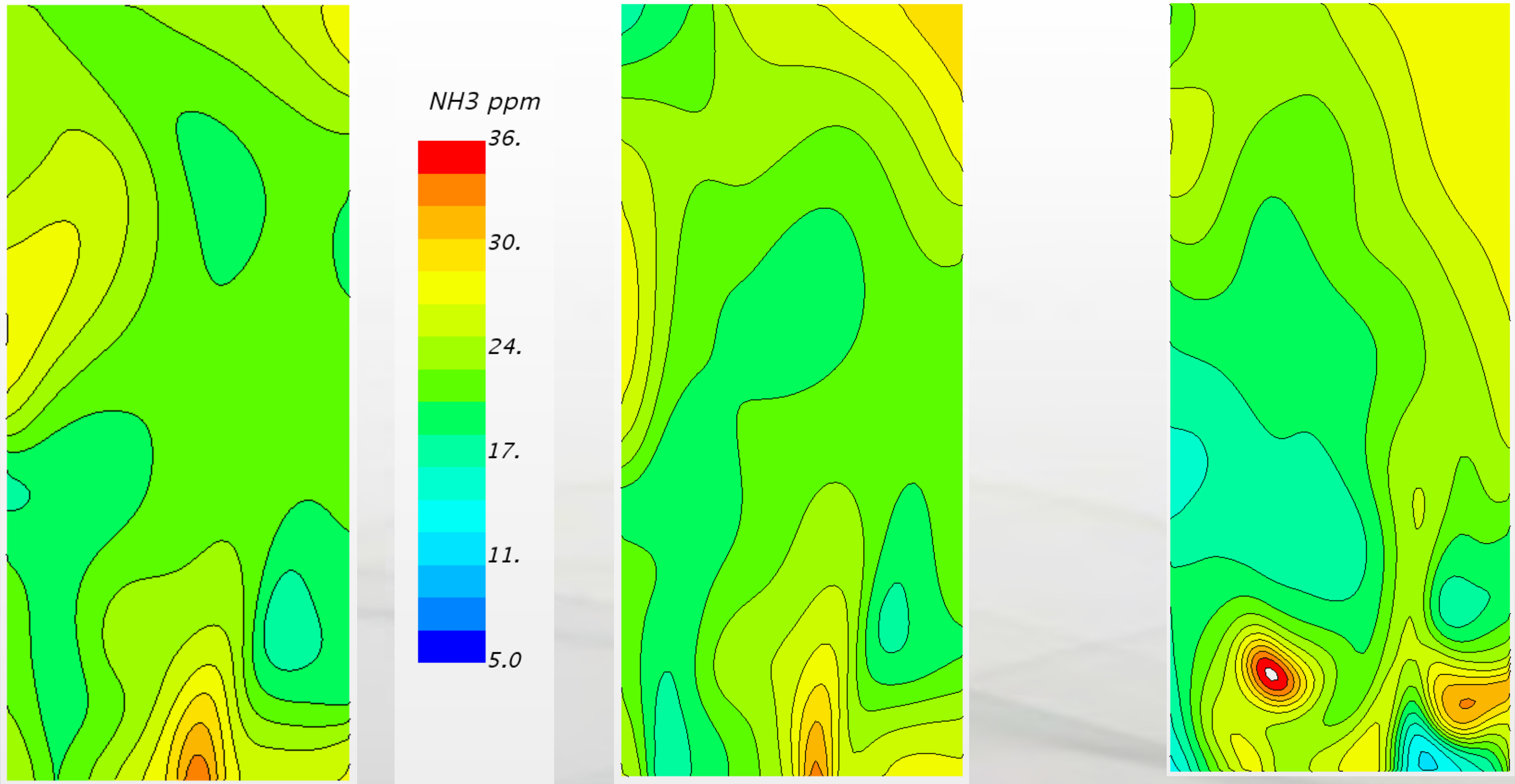
No mixers
RMS = 30%

2x2 array of mixers
RMS = 10%

Altering the blade angles of the mixers can reduce dP



Trade off mixing performance for pressure drop



2x2 array std design
NH_3 RMS = 10%
Vel RMS = 7%
dP =1.00” wc

Top 2 mixers low dP
NH_3 RMS = 11%
Vel RMS = 7%
dP =0.77” wc

All mixers low dP
NH_3 RMS = 15%
Vel RMS = 10%
dP =0.48” wc

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Discussion of results

- **Even though the case without mixers was challenging to optimize it is still a good example of the benefits of adding mixers to a system**

- **These systems are complex and require a high degree of application specific engineering to meet performance standards**

Case	Delta p above no mixer (in wc)	Velocity RMS at HX face (%)	NH3 RMS at HX face (%)
No mixers	0	14	30
4x4 array of std mixers	1.02	7	NA
2x2 array of larger mixers	1.00	7	10
2x2 array with top row low dP	0.77	7	11
2x2 array with all low dP	0.48	10	15

Future work

- Model validation
- Add region downstream of duct burners through catalyst to CFD model
- Modeling of “Asian/ European” style évasé
- Perf plates, other mixer types
- Utilize optimization algorithms built into CFD program

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Graphics courtesy of LP Amina

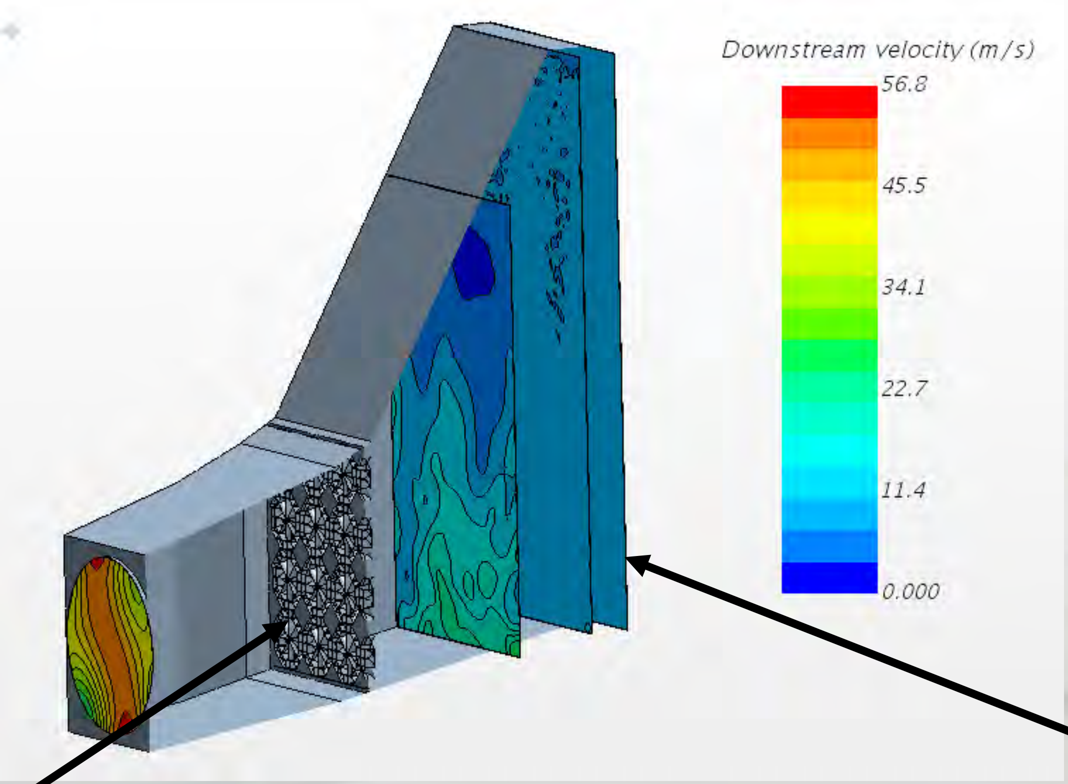
Acknowledgements

- We would like to thank Matt Zedler and LP Amina for providing model geometries and guidance on this project

Questions?

Appendix 1: Velocity profiles of different mixer configurations

Blenders significantly reduce variation in velocity profile

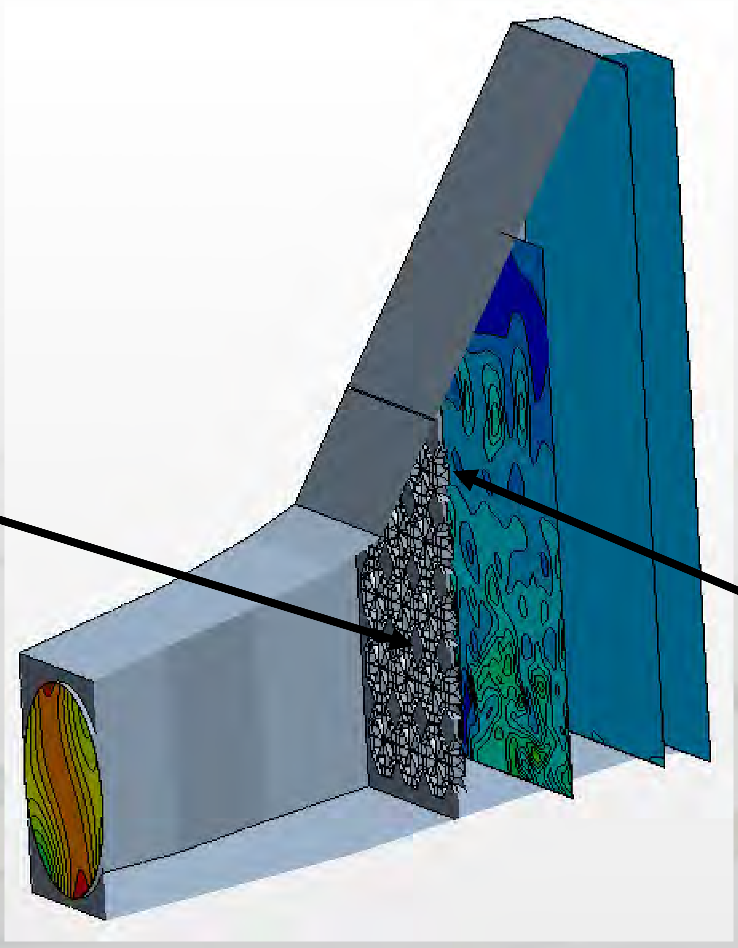


Velocity RMS at outlet = 7%
w/o mixers= 14%

Mixers

Mixer ΔP ≈ 1.02” wc

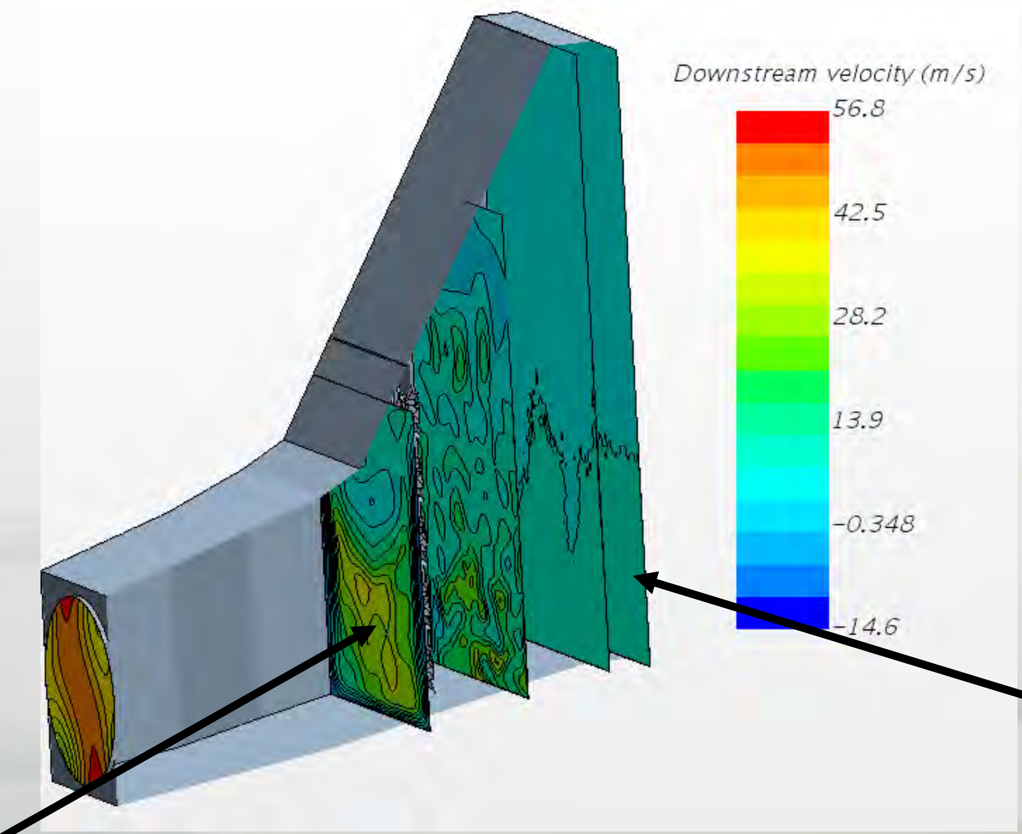
4x5 array with low dP mixers on top row



Mixer array moved downstream

Top row of mixers have less aggressive blade angles

4x5 array with low dP mixers on top row

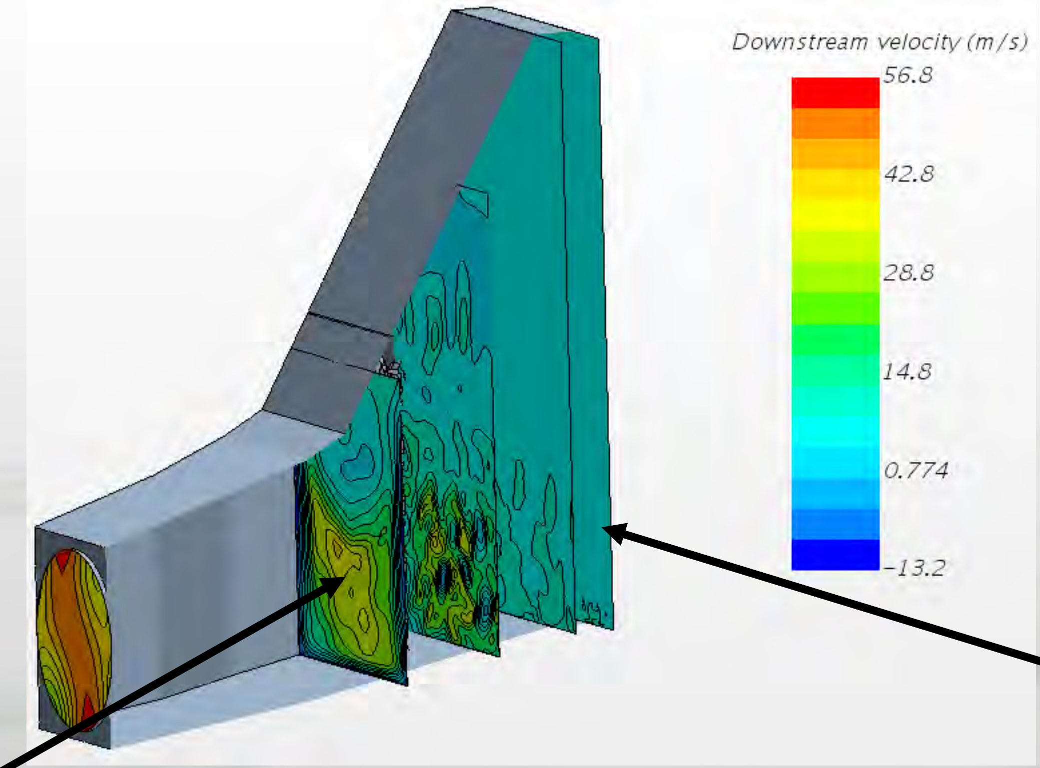


Velocity RMS at outlet = 8%

Mixers

Mixer ΔP ≈ 0.86” wc

4x5 array with all mixers low dP



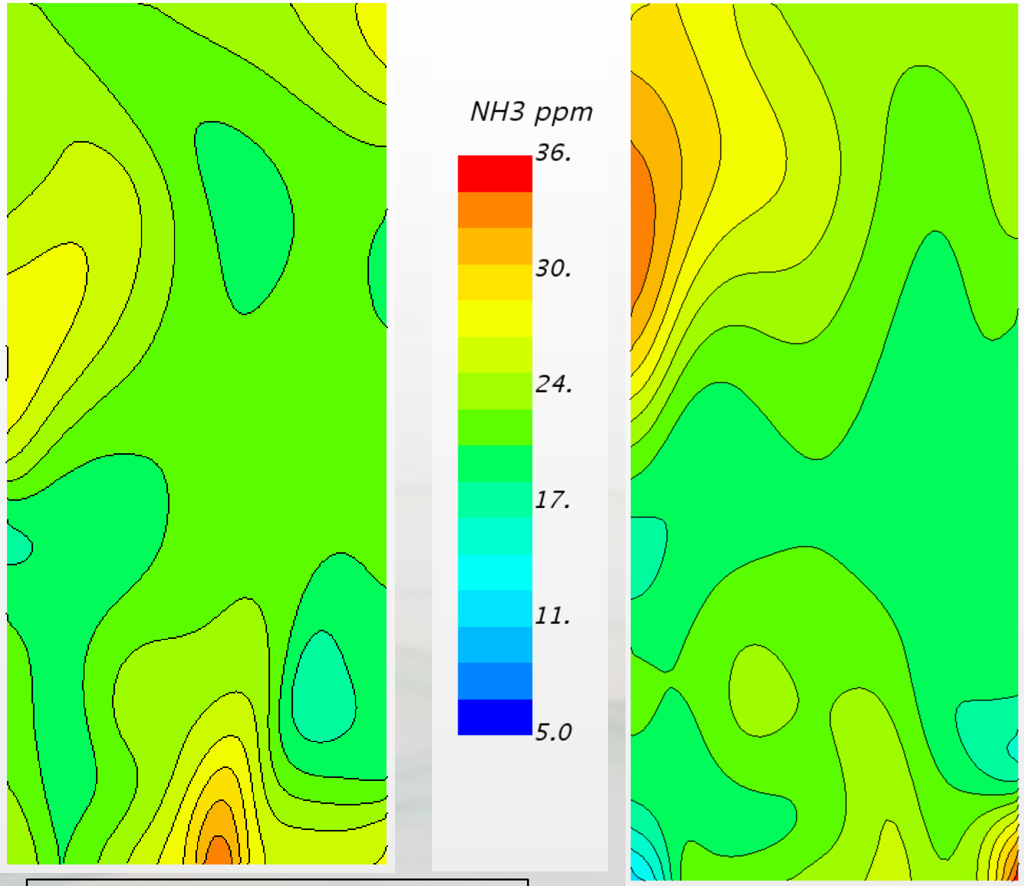
Velocity RMS at outlet = 10%

Mixers

Mixer ΔP ≈ 0.52” wc

Appendix 2: Effects of rotating inlet velocity profile

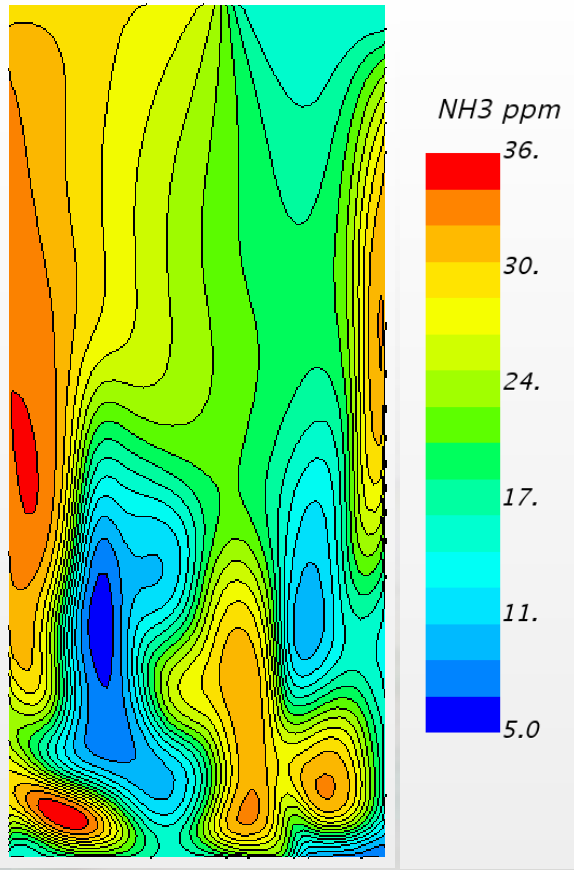
Inlet velocity profile clocking with mixers



Array of 4 mixers
NH_3 RMS = 10%

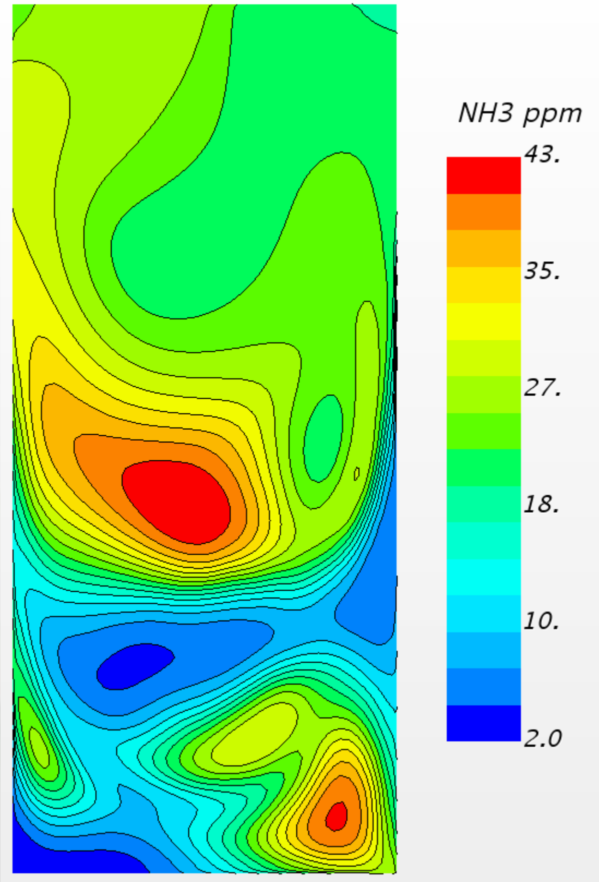
Profile rotates 90 deg CW
NH_3 RMS = 14%

Inlet velocity profile clocking no mixers



Base case

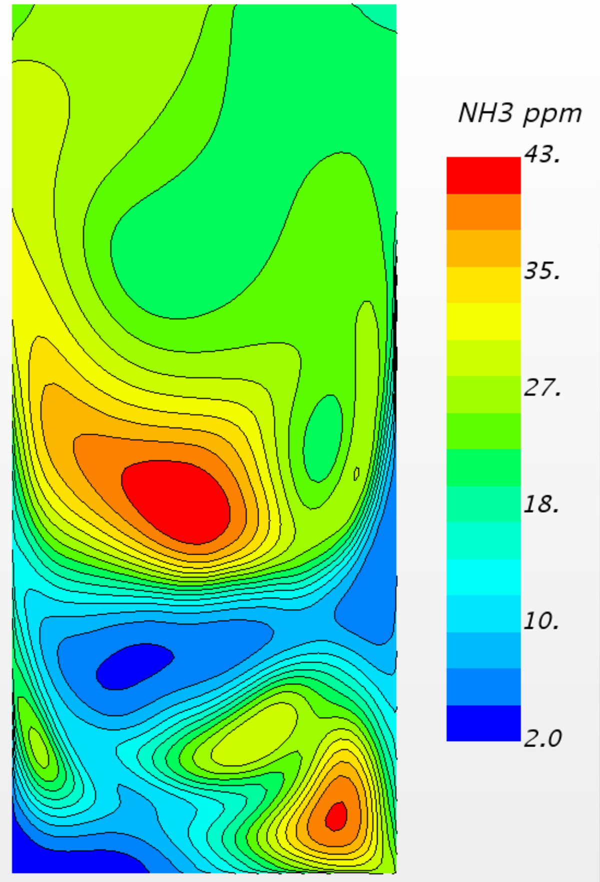
NH_3 RMS = 30%



Profile rotates 90 deg CW

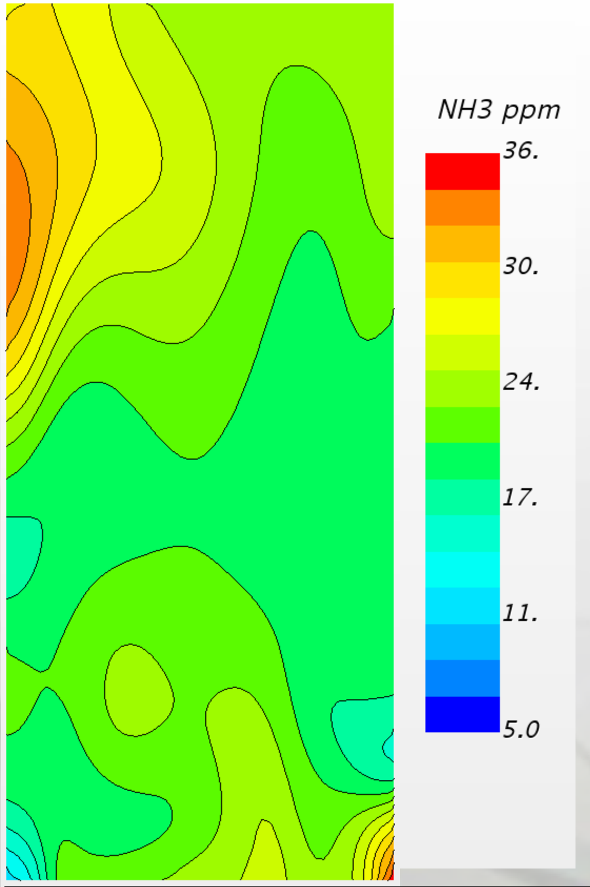
NH_3 RMS = 40%

Inlet velocity profile clocking no vs with mixers



Without mixers

NH_3 RMS = 40%



With mixers

NH_3 RMS = 14%