Component Level Modeling of Materials Degradation for Insights into Operational Flexibility of Existing Coal Power Plants

Anand Kulkarni, Siemens Corporation

DOE Award: DE-FE-0031831

Acknowledgements

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Outline

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- Project Objective and Team
- Project Approach to Meet Technical Targets
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- Task 3.0 – Fireside corrosion/steam oxidation/creep modeling of superheater/reheater tubes
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- Task 5.0 - Modeling Data Validation and Scale-up Opportunities
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- Project Schedule and Milestones

Synergistic research for component level modeling for insights into operational flexibility of existing coal power plants

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Project information

PI: Anand Kulkarni

Funder: DOE Office of Fossil Energy (FE) – NETL Crosscutting

Strategic Partner: Siemens Gas and Power, Cranfield University

Total Project Funding: $937.5K ($750K Federal/$187.5K Cost share)

Project Details

- **Generate CFD/FE models for the prediction of deposition/erosion/corrosion around the fireside surfaces of a superheater/reheater boiler/heat exchanger tube.**
- **Generate CFD/FE models predicting the extent of steam oxidation within a heat exchanger tube or steam pipe, and the impact that plant cyclic operation will have on oxide spallation.**
- **Generate CFD/FE models for multiphase fluid flow predicting water droplet erosion for last stage low pressure turbine blade.**
- **Determine the impact of plant operations (fuel/operational flexibility), validated with service feedback data using plant and pilot-scale rig data (where available), on the response/trends of the three component/material CFD/FE models generated.**

Technical Highlights

Funding Opportunity Objective	Objective of the Proposed Work
Advanced modeling tools for existing power plant issues and mitigation	Component level modeling utilizing computational fluid dynamics for materials degradation for existing coal power plant issues
Insight into existing coal plant challenges and mitigation solutions	Modeling activities will focus on 1) Creep/fireside corrosion/erosion/steam oxidation in superheaters/reheaters and steam pipework and 2) water droplet erosion resulting in fatigue failure of last stage steam turbine blades
Materials degradation for operational flexibility	Multidisciplinary models for for solid particle impingement/ oxide scale exfoliation within the boiler tubes and dropler impingement in steam turbine to be evaluated with stress changes due to cyclic operations
Analytics results from model validated from plant data	Validation of modeling results via service run data (destructive metallurgical analysis) to correlate model and design assumptions to actual power plant performance

The proposed innovation is in developing a computational fluid dynamics/finite element (CFD/FE) modeling toolkit for the component level models to tackle multidisciplinary failure mechanisms occurring concurrently for extreme environment materials. Lifetime assessment in such environments also needs to account for the unit-specific analyses, operational history and fuel feedstock; this can only be obtained by destructive analysis of components. This, in turn, enables validation of the model toolkits utilizing service feedback data, improving the probability of time/temperature dependent life prediction.

Project approach for component modeling for existing power plants

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Year 1 Computational CFD/FE toolkit Framework	Year 2 Model simulation for Multidisciplinary failure mechanisms	Year 3 Heat exchanger and steam Turbine Component model Validation with plant data
Technical Progress Computational CFD/FE for failure mechanisms observed. Plant operations data for existing power plants as input for computational simulations	**Technical Progress** Computational tools developed for life calculations to accommodate baseload and cyclic operations Basis for design alternative to operational flexibility	**Technical Progress** Validation of CFD/FE computational models with plant data Validated life assessment methodology for heat exchanger and steam turbine
Go / No-Go CFD/FE toolkit framework with plant operations data and component performance and issues	**Go / No-Go** Develop one stop tool interface for model liking to design data and FEA package for component model analysis	**Program Success** Integrated framework established for robust life prediction assessment for operational flexibility and future plans

Development approach to advance technology

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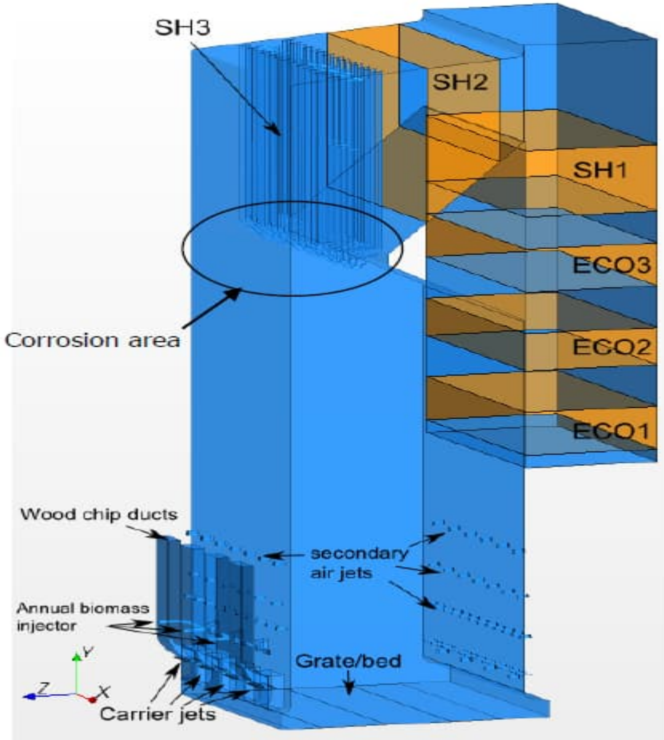
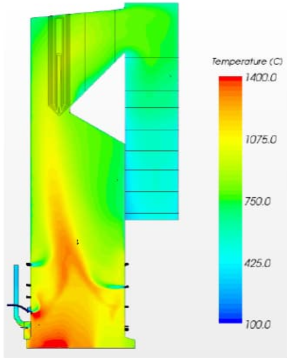
Simulated domain containing the boiler with super heater and economizers

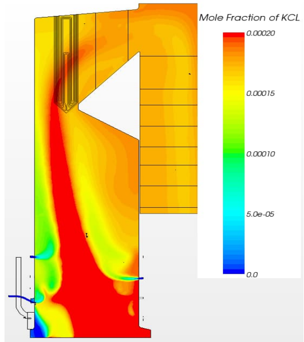


Svend S. Petersen, Master Thesis, 2012

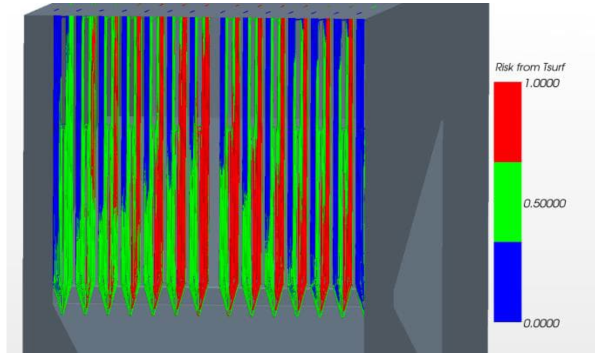
Temperature profile



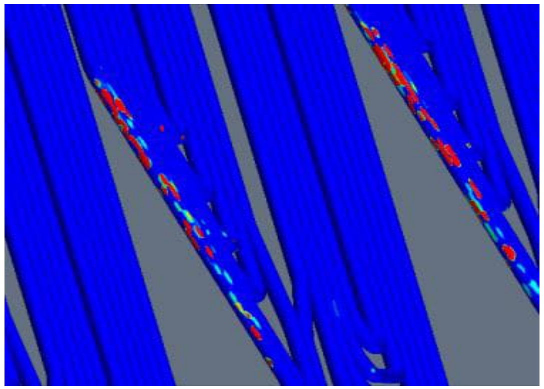
Concentration of KCl



corrosion risk on the SH3 surface



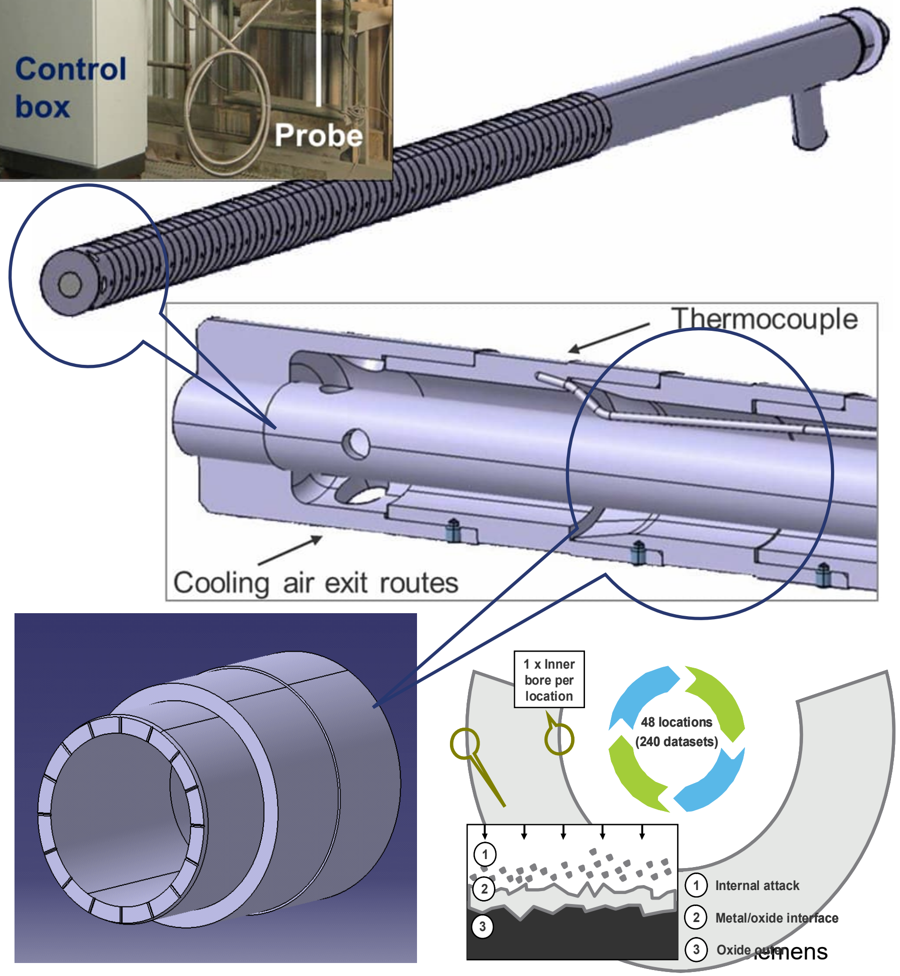
Prediction of ash buildup on SH3 on front side facing flow



Simulation models for corrosion to predict localized high risk corrosion areas – Monitoring, Mitigation and Reduced repair costs/Forced Outages

Task 2.0 - Collect boiler/steam turbine plant operating data

- Data gathered on plant component materials degradation to establish CFD/FE model framework
- Data from exposures previously carried out in UK power plants (e.g. Tilbury, Ironbridge, Ratcliffe) for 'Innovate UK' projects (ASPECT and ASPIRE), EU NEXTGENPOWER project and earlier superheater/reheater tube monitoring
- Data include fireside corrosion damage measurements from inspections of heat exchanger tubes operated in pulvisered coal fired power plants as well as temperature-controlled probes of materials/components installed in plants for evaluation.
- Datasets gathered includes fuel compositions and operating environments – but every exposure has gathered different sets of exposure parameters
- Datasets allow the range of exposure conditions and alloy/coating fireside corrosion in superheater/reheater tubes in historic coal-fired UK pulverised fuel power stations to be quantified
- These data feed into the development/validation of fireside corrosion model (part of Task 3.2).



Task 3.0 – Fireside corrosion/Steam oxidation/Creep modeling of Superheater/Reheater tubes

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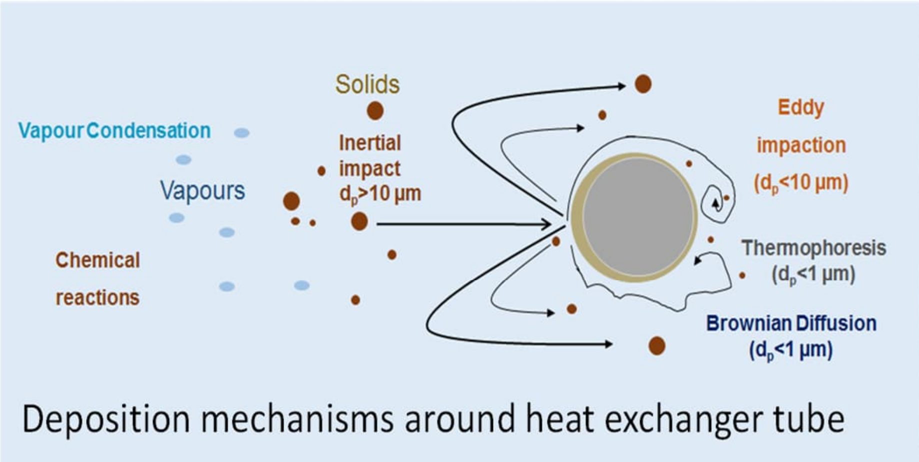
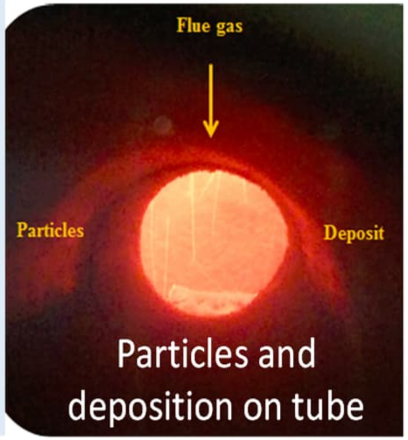
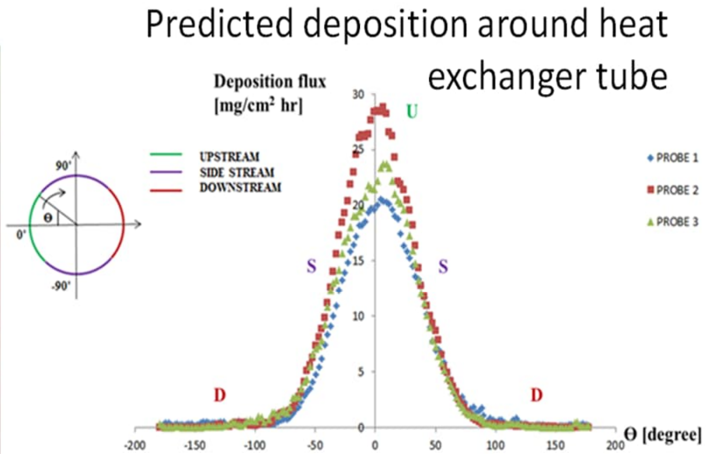
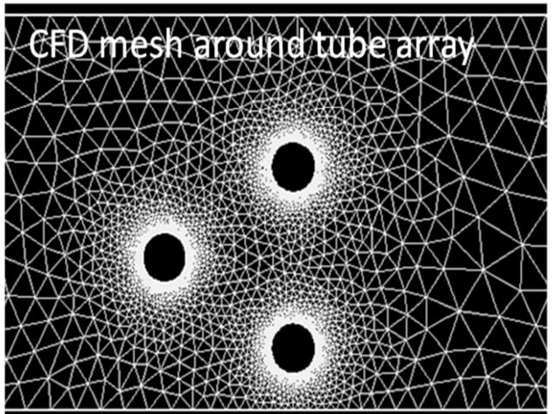
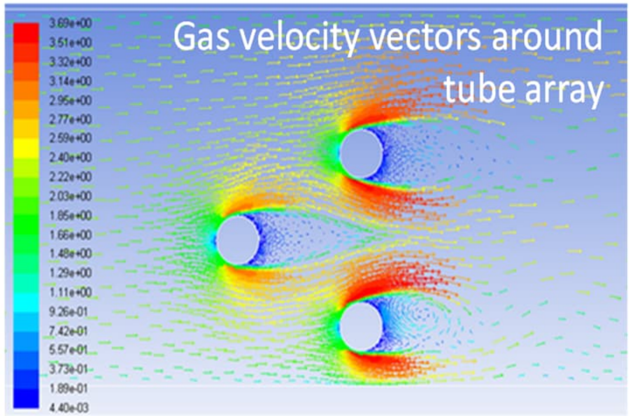
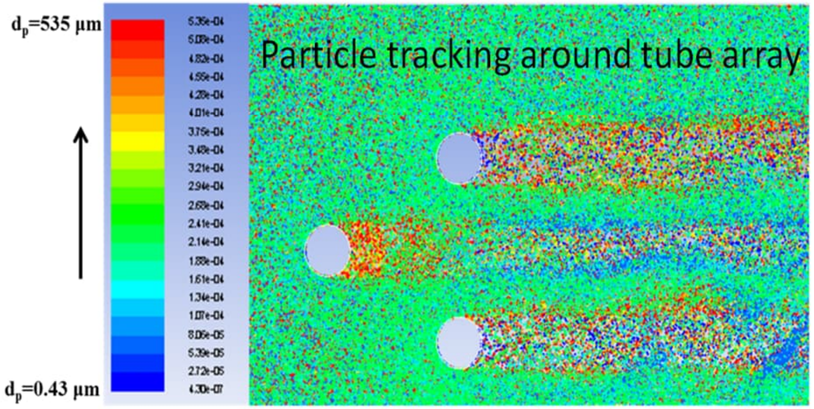










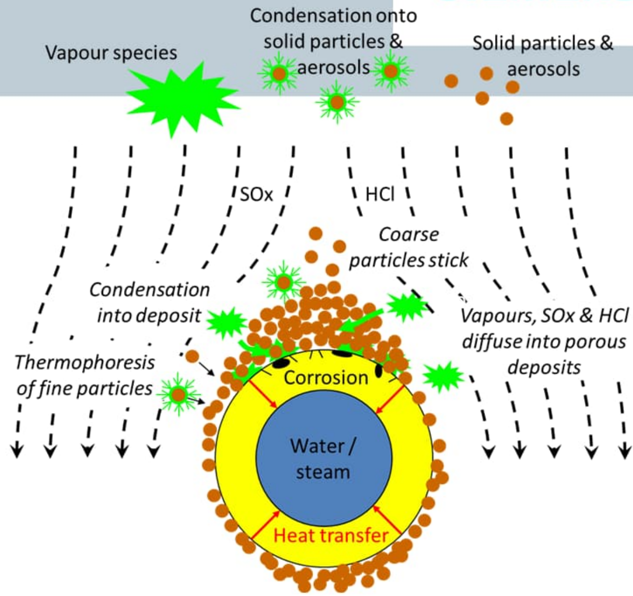


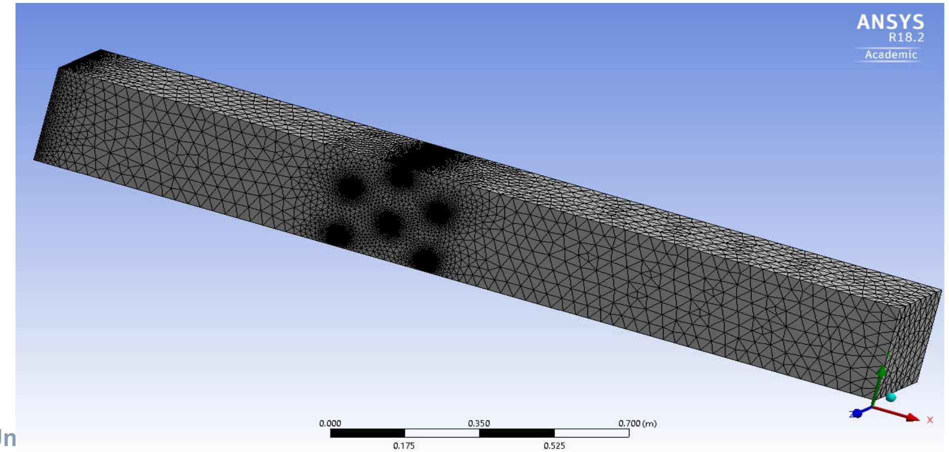
Updated - deposition modelling

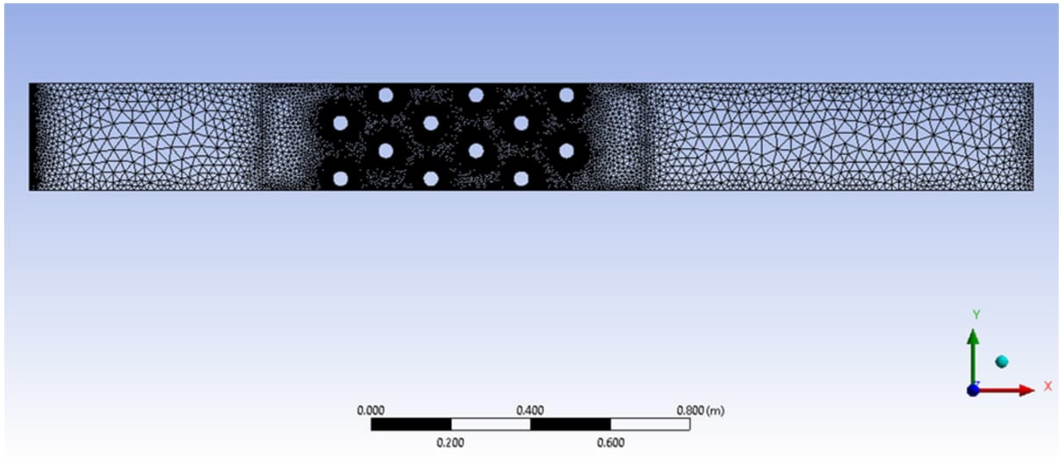
Starting point: 2D Fluent deposition model

Developments:

- Tube numbers increased from 3 to 12
- Model reconfigured from 2D to 3D geometry
- Alkali vapour condensation model updated with new parameters
- User defined functions (UDFs) updated and operations verified for both 2D and 3D cases
- Fluent code now on High Performance Computer (HPC)
- Siemens STAR-CCM+ software on desktop computer to investigate equivalent simulations compared to the Fluent



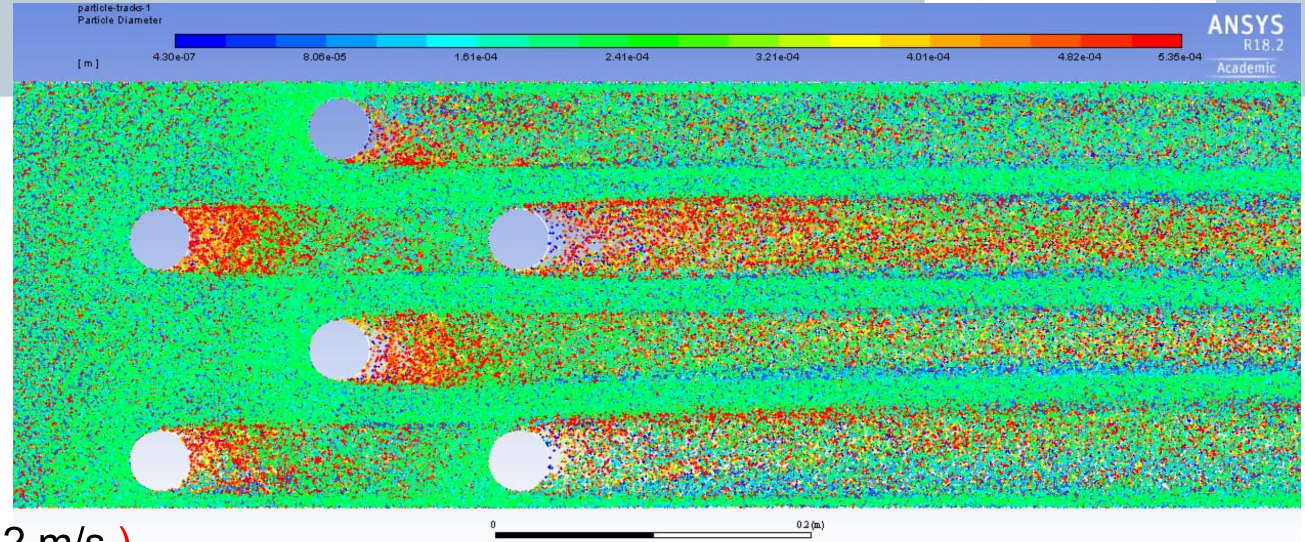




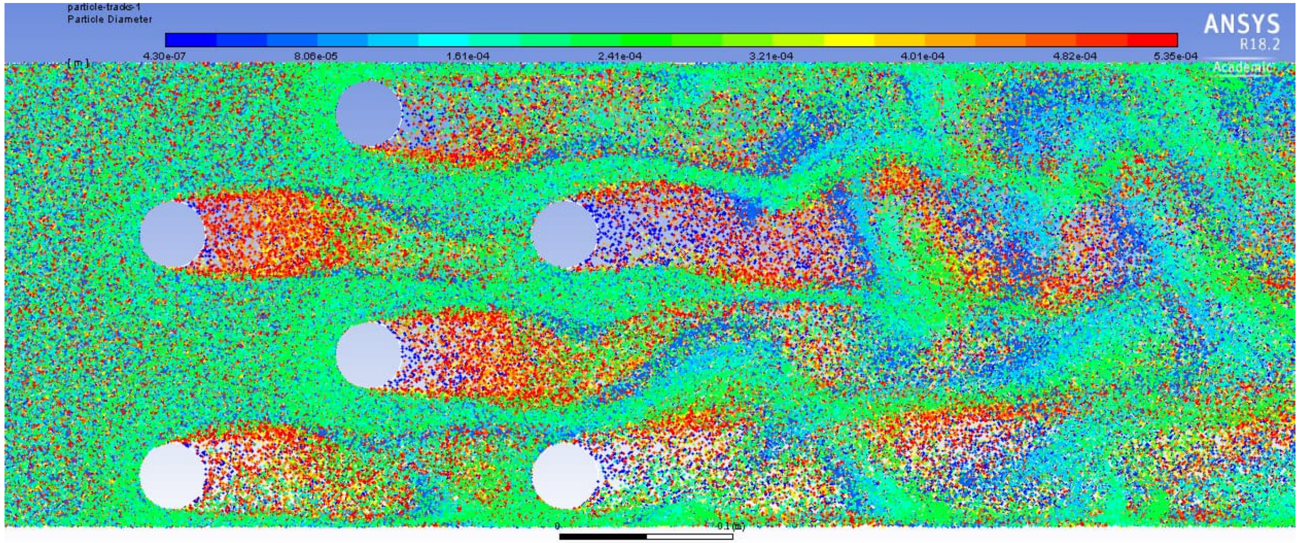
Deposition on tubes

- Fluent files now moved to Cranfield HPC to enable simulation of longer times
- 2D simulations:
  - 6 tubes & 12 tubes
  - Rosin-Rammler particle size distribution
  - Investigating model sensitivities to input conditions

Particle Diameter Distribution (flue gas velocity = 10 m/s)



Particle Diameter Distribution (flue gas velocity = 2 m/s)



- Ash mass flow - 0.0001 kg/s
- Particle minimum diameter – 0.43 μm
- Particle maximum diameter – 535 μm
- Particle mean diameter – 68 μm
- Rosin Rammler spread parameter – 1.07
- Temperature – 1273 K
- Pipe temperature – 773 K
- Na_2SO_4 concentration in flue gas – 1 ppm

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Flow visualization over the tubes (2D)

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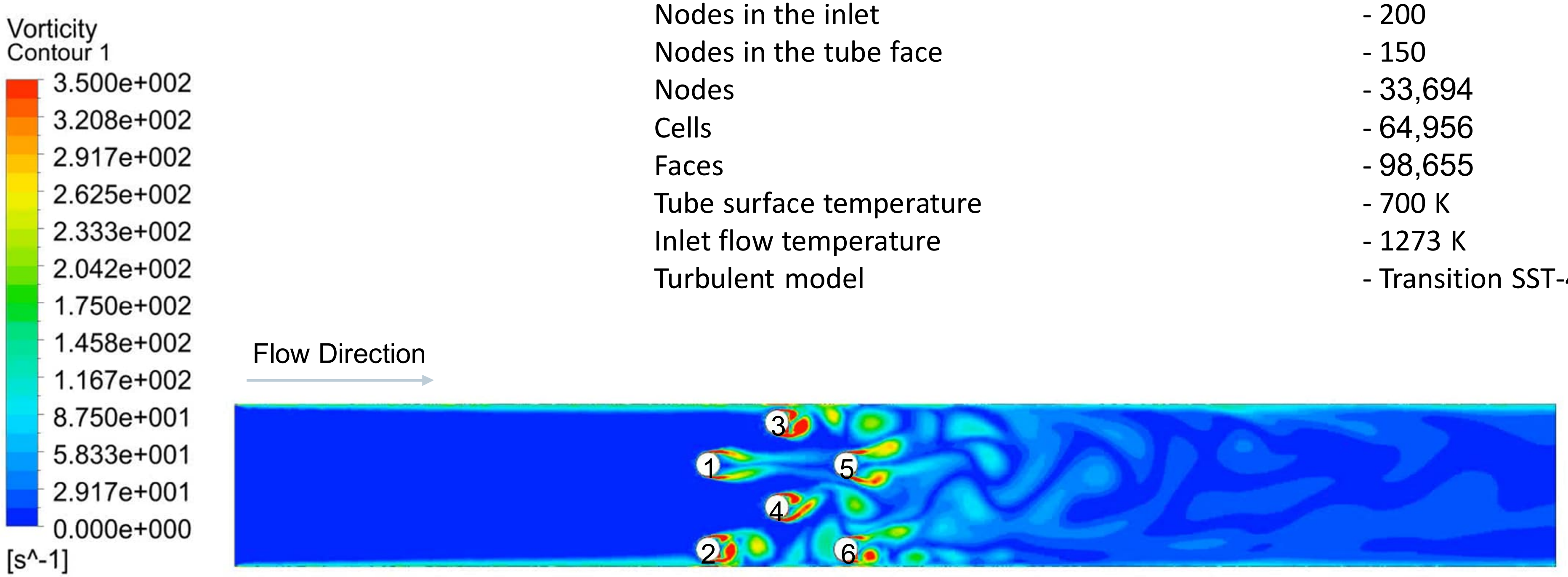
Inlet Velocity	- 2 m/s
Nodes in the inlet	- 200
Nodes in the tube face	- 150
Nodes	- 33,694
Cells	- 64,956
Faces	- 98,655
Tube surface temperature	- 700 K
Inlet flow temperature	- 1273 K
Turbulent model	- Transition SST-4



Vorticity is a measure of the rotation of a fluid element as it moves in the flow field – it is defined as the curl of the velocity vector

2D Model sensitivity to input conditions

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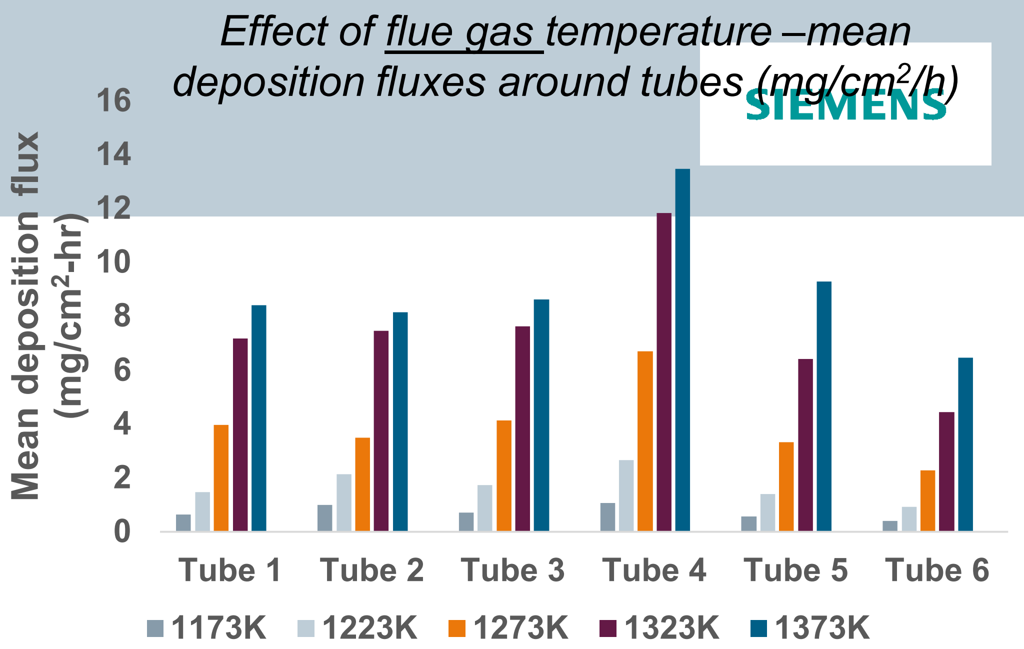
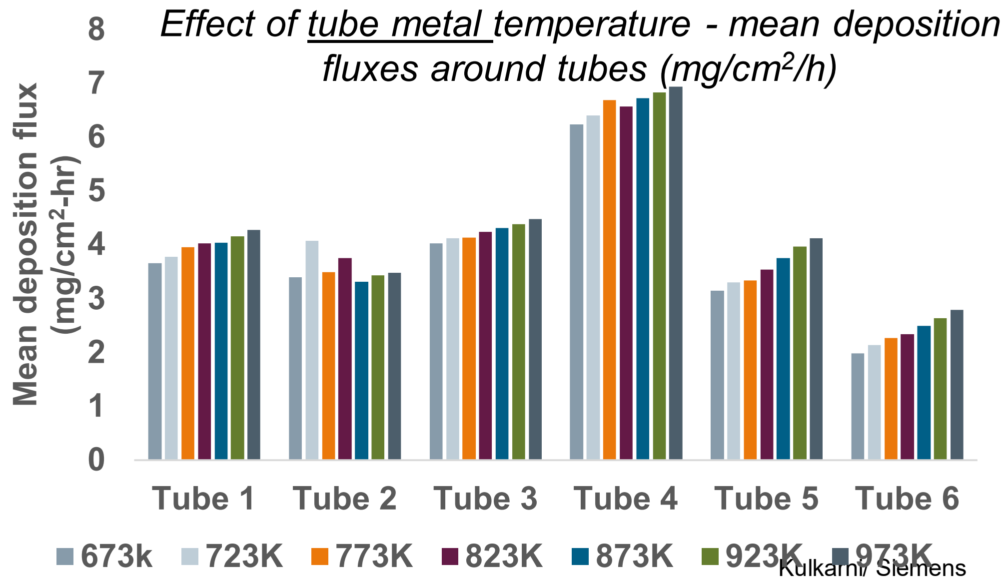
Parameter variations investigated:

- Geometry – 2D
  - Numbers of tubes – 3, 6, 12
- Flue gas velocities – 2 and 10 m/s
- Alkali sulphate concentrations
  - 1, 5, 10, 50, 100, 500, 1000 ppm
- Simulation times
- Numbers of nodes / mesh resolutions
- Temperature
  - Flue gas – 1173, 1223, 1273, 1323, 1373 K
  - Tube surface – 673, 723, 773, 823, 873, 923, 973 K

Fixed parameters:

- Ash mass flow - 0.1 g/s
- Particle minimum diameter – 0.43 μm
- Particle maximum diameter - 535 μm
- Particle mean diameter – 68 μm
- Rosin Ramler Spread Parameter - 1.07





3D deposition modelling

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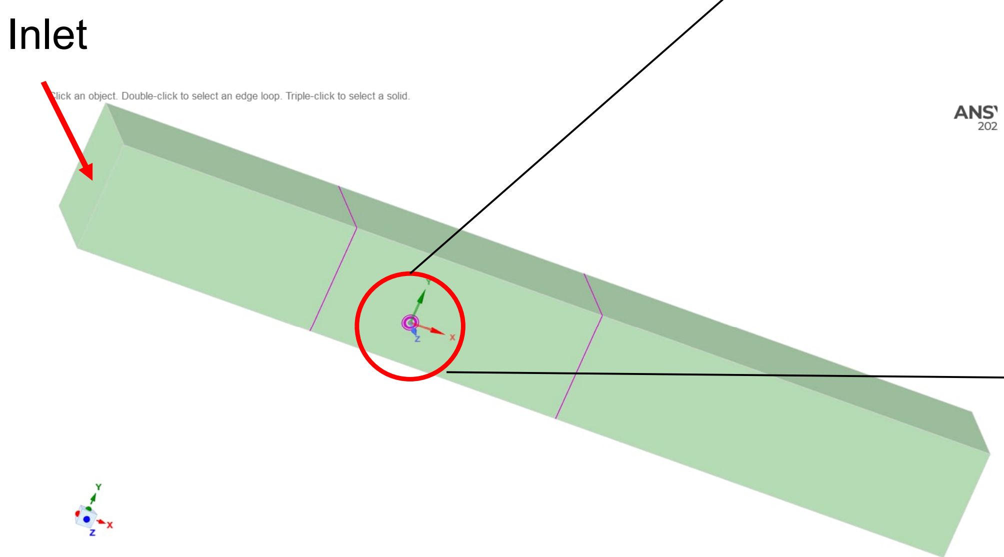
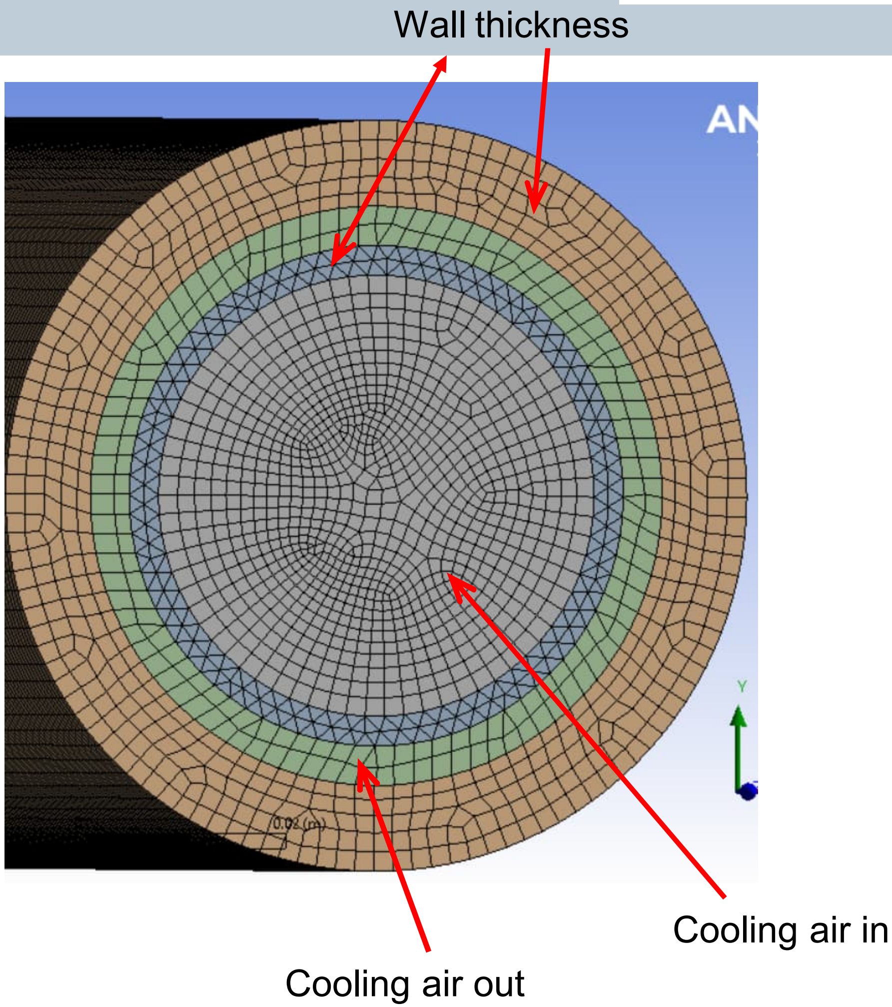
- Working towards deposition around probe in 3D
- Internal structure and cooling air flow geometry mesh:
  - Completed for 3D case
  - Dimensions from constructed bayonet probes
- Calculations being performed in stages:
  1. Simulation of flow fields and temperature distributions
  2. Introduction of ash particles and vapour deposition





3D air cooled probe - one tube simulation

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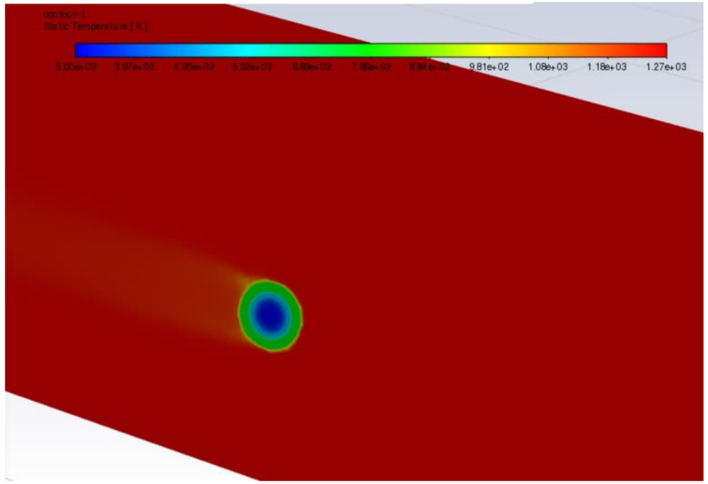
Boundary condition

Flue gas:	Cooling air:
inlet velocity- 2 m/s	inlet velocity- 2 m/s
inlet temperature- 1273 K	inlet temperature- 300 K

- Next steps in Fluent:
  - injection of ash particles and vapour species
- Simulation in Star CCM+ has started.

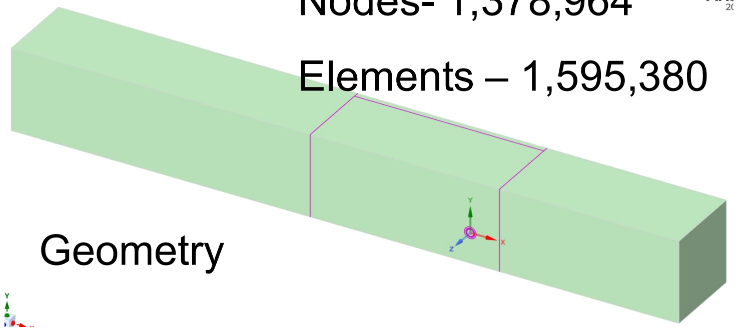


Temperature (2D cut plane)

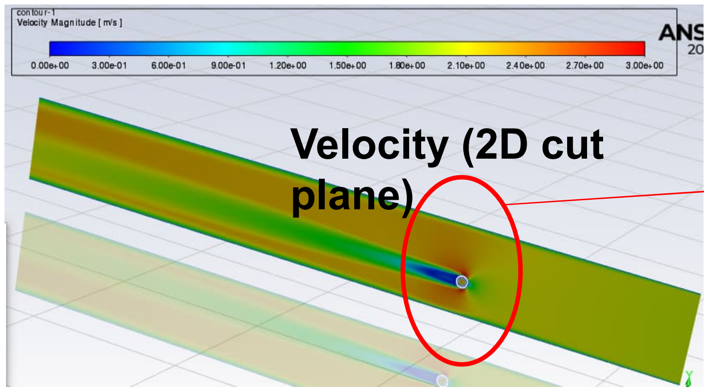
Mesh

Nodes- 1,378,964

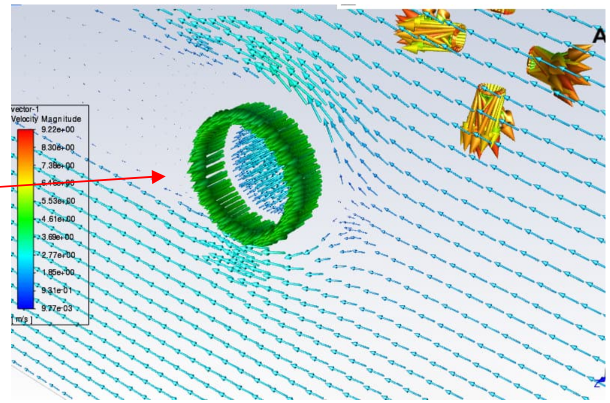
Elements – 1,595,380



Geometry



Velocity (2D cut plane)



L0 Titanium blade trailing edge erosion
Background

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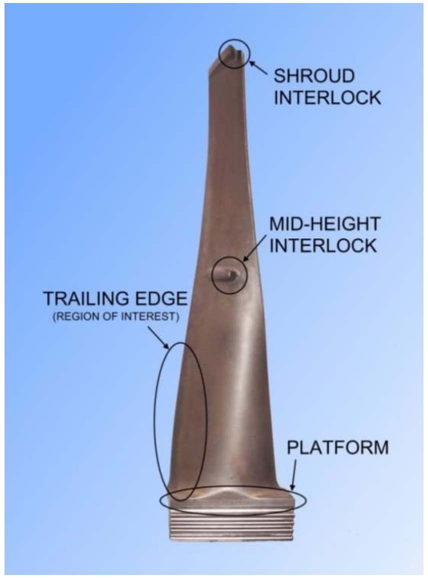
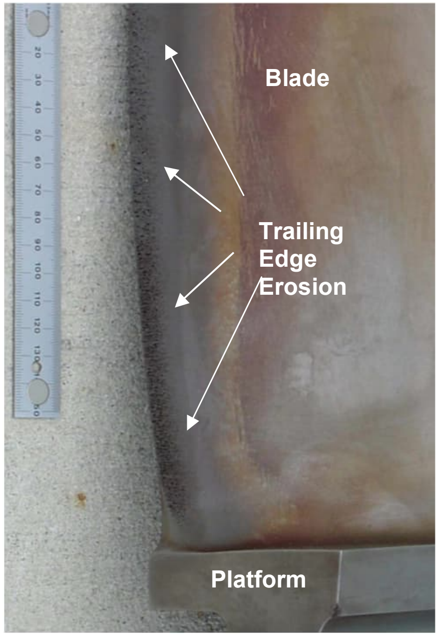
Trailing Edge Erosion

Observed on the convex surface of the airfoil on all current styles of last row titanium blades on some units.

The erosion observed has varied, but in some cases has extended from the portion of the airfoil trailing edge just above the blade platform to as high as the mid-height interlock.

Blade airfoil cracks have been observed to initiate in the lower third of the airfoil.





Cracks originating in a heavily eroded region of the trailing edge have led to blade separation events on some units

Titanium blade trailing edge erosion contributors

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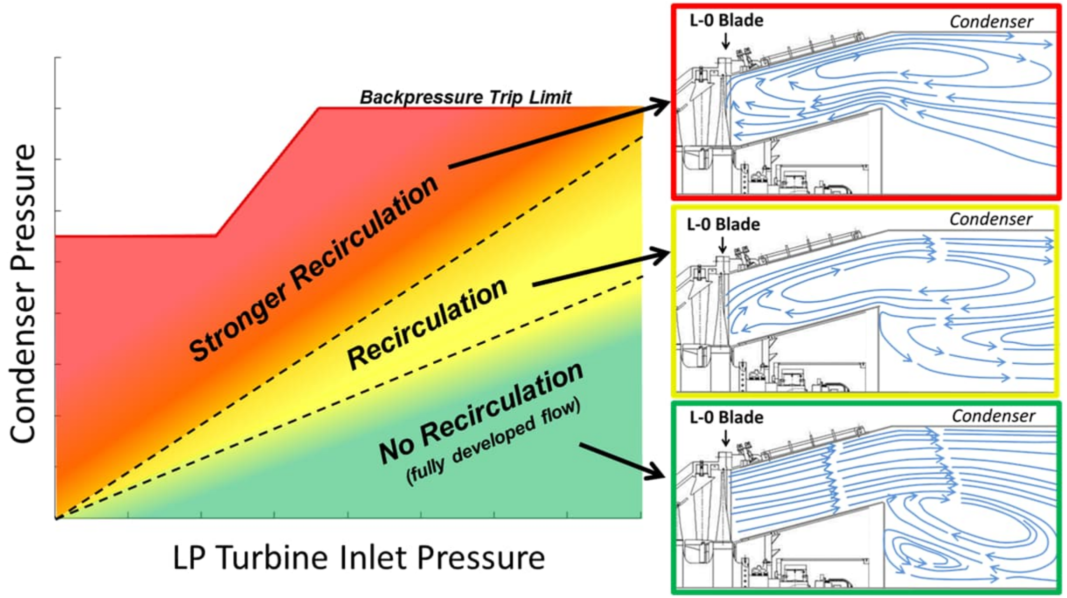
Exhaust Recirculation

- Recirculation can occur during low load or part load operation and is influenced by elevated backpressures
- Figure to right illustrates general relationship between steam turbine flow, condenser backpressure, and exhaust recirculation

Exhaust Recirculation as a Function of LP Inlet Pressure and Condenser Pressure

(General illustration only. Not to scale)



In general, as backpressure increases for a given load, the potential for flow recirculation increases

10.3m² Titanium Blade Trailing Edge Erosion Contributors

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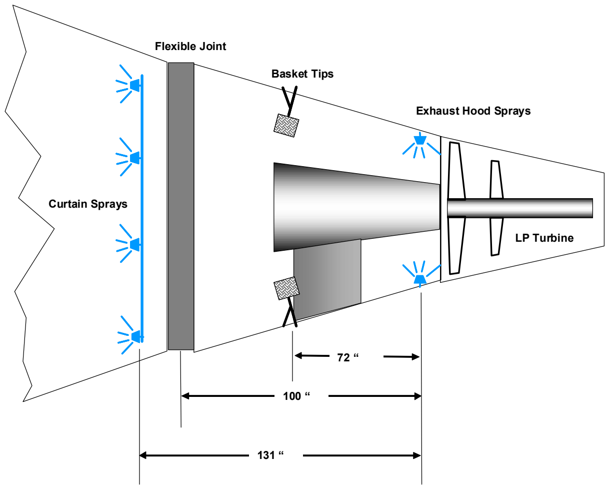
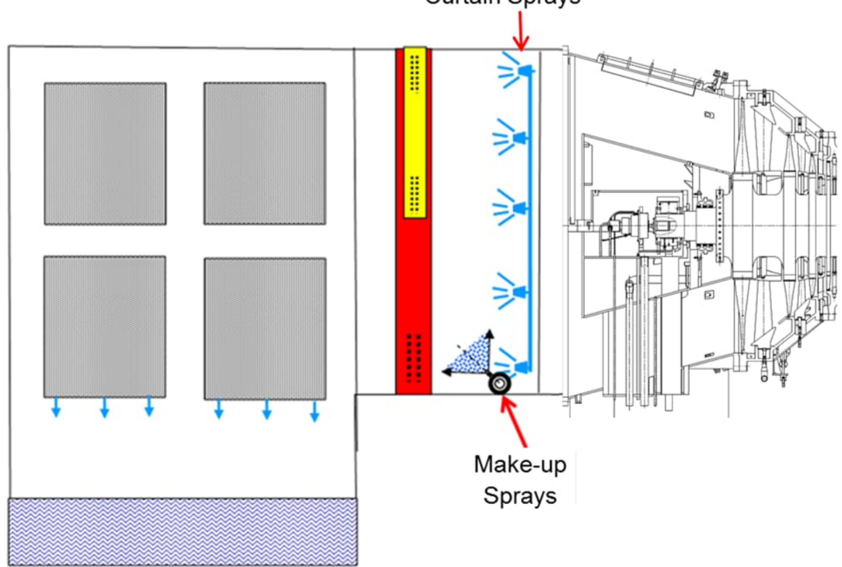
Downstream Moisture

- The layout and operation of the condenser, including the steam bypass system and the associated condenser spray systems, have been identified as factors in the amount of downstream moisture available to be recirculated back toward the turbine
- These spray systems, depending on their orientation and location in a particular unit, can provide the moisture necessary for erosion to occur



Curtain Sprays are located approximately 12 feet from the L-0 blades.

Nozzles are oriented away from the steam turbine..



Example Moisture Sources in Condenser

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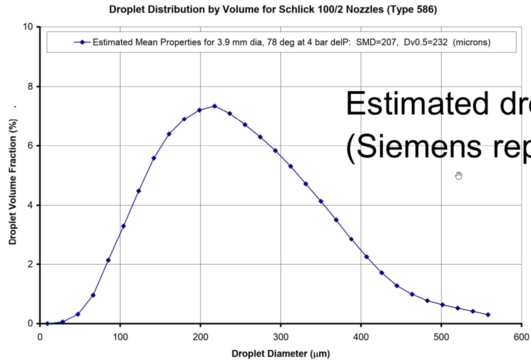
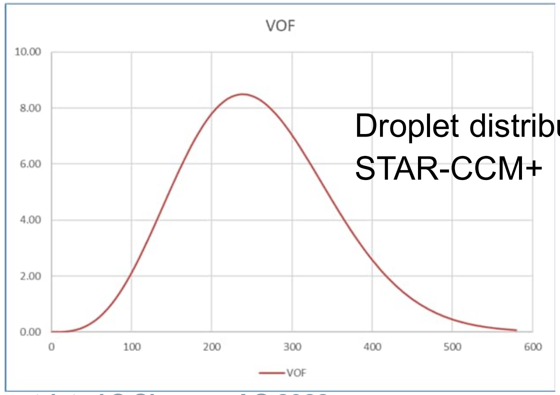
Boundary conditions:
Droplets injection

- <u>Droplets Injection Boundary Conditions</u>

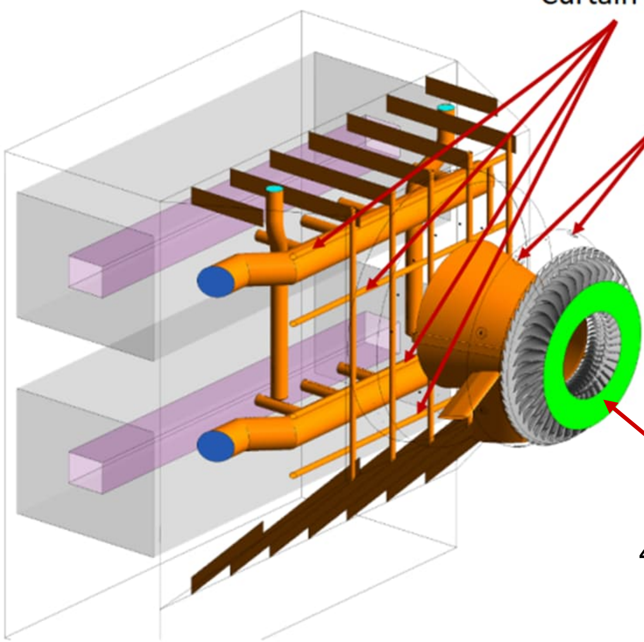
From the hood spray nozzles



Estimated droplet distribution (Siemens report)

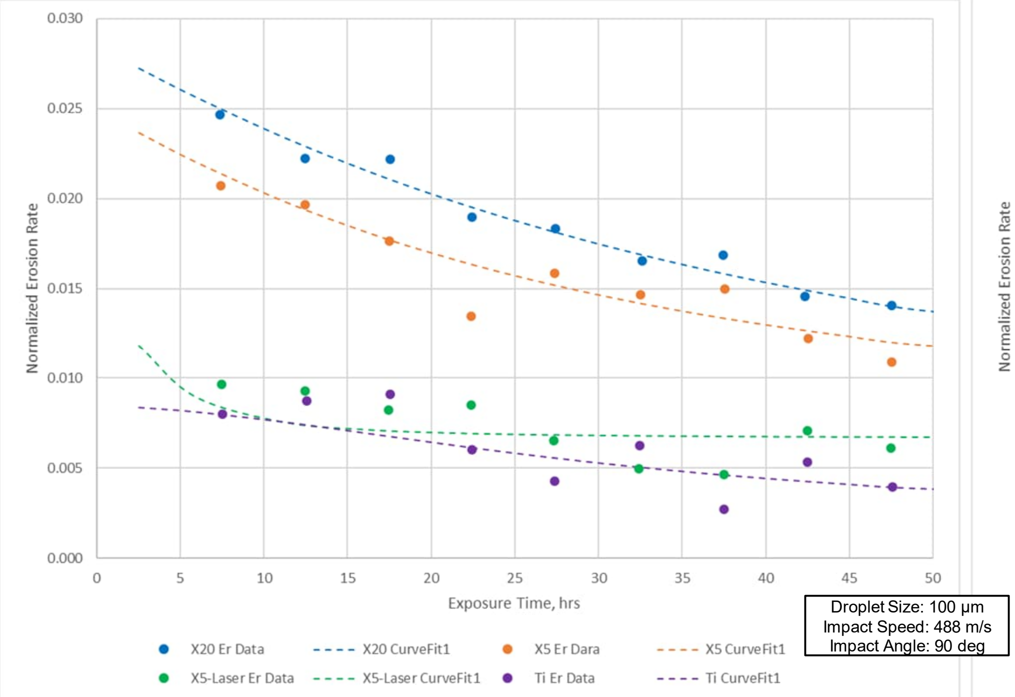


Droplet distribution applied in STAR-CCM+

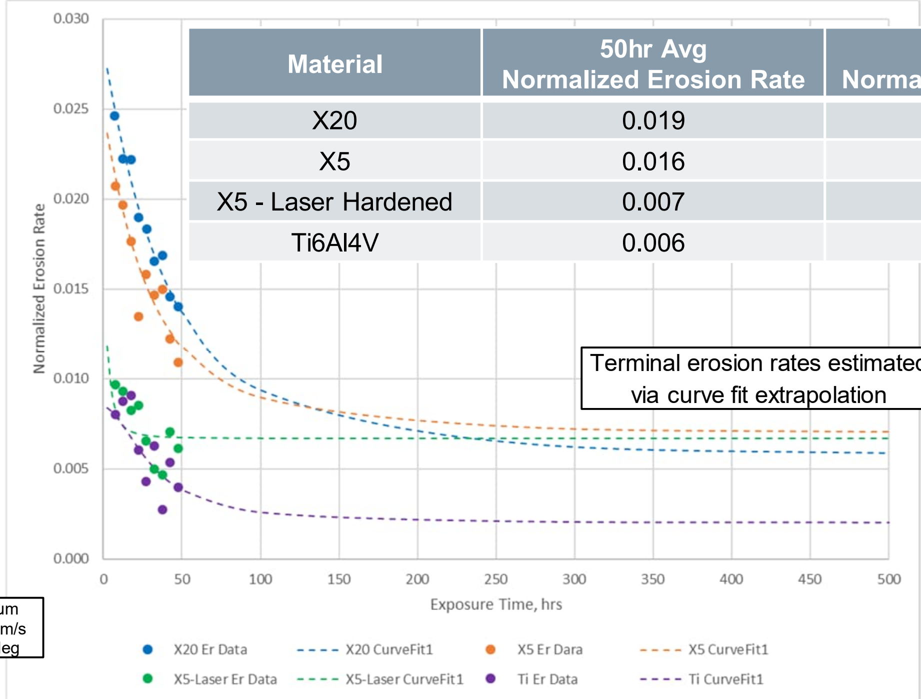


Normalized Erosion Rates

Experimental Data



Extrapolated Data



Material	50hr Avg Normalized Erosion Rate	Terminal Normalized Erosion Rate
X20	0.019	0.006
X5	0.016	0.007
X5 - Laser Hardened	0.007	0.007
Ti6Al4V	0.006	0.005

Erosion correlations are created using 50 hr average and terminal rates

Blade Erosion

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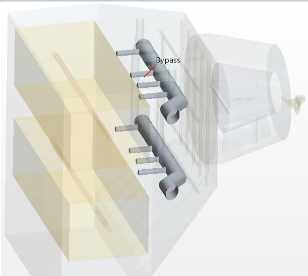
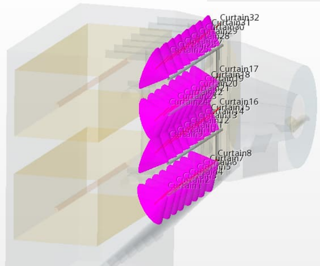


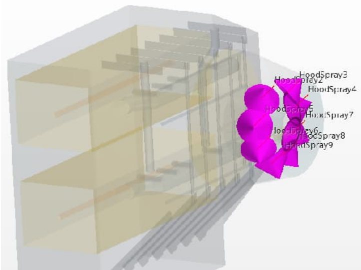
Bypass Injectors

	ErosionRate (kg/s)			
	Blending Lower	Blending Upper	Hot Start Lower	Hot Start Upper
ByPass	3.96E-14	1.62E-14	7.61E-14	1.43E-14
Curtain	5.77E-14	2.03E-13	1.11E-12	4.59E-14
Diffuser			1.92E-12	1.16E-12
OverAll	9.73E-14	2.19E-13	3.11E-12	1.22E-12

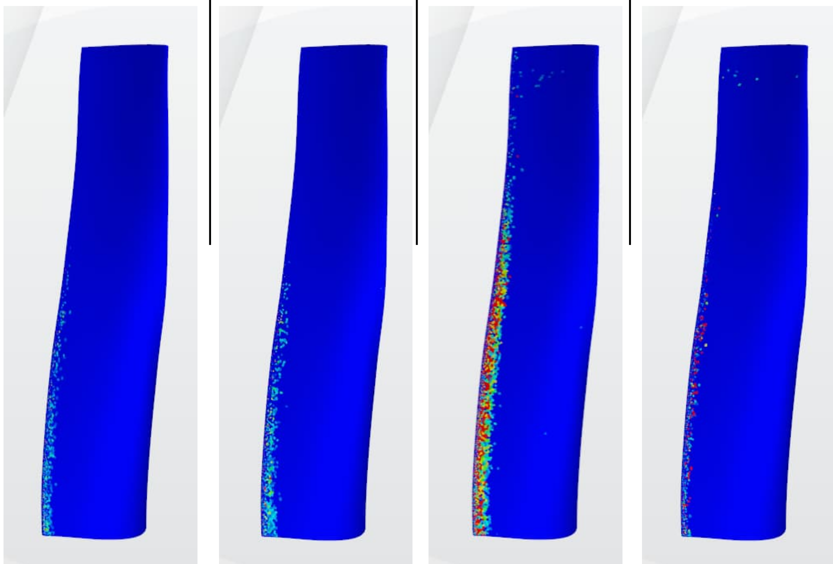
- The closer the water droplet spray source is to the turbine, the larger the erosion impact
- Diffuser hood spray is the largest contributor
- Erosion rates represent 50 hr average dataset for Ti6Al4V

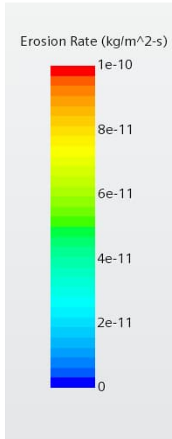


Curtain Spray Injectors



Hood Spray Injectors





Blade erosion rates calculated for each droplet source then combined ("OverAll")

Task 5.0 - Modeling data validation and scale-up opportunities

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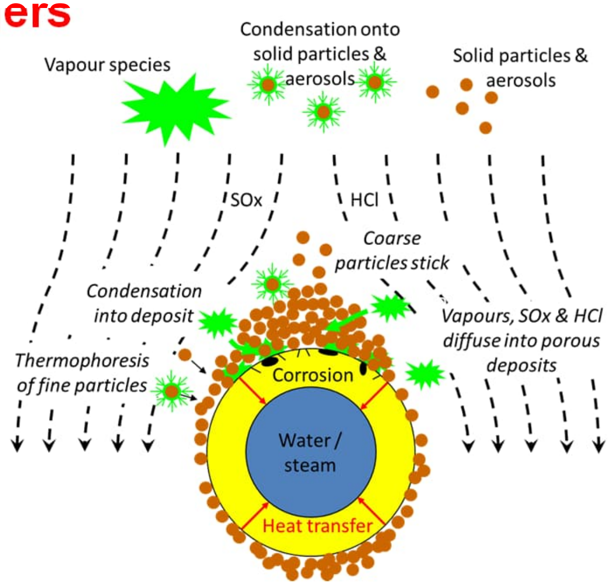
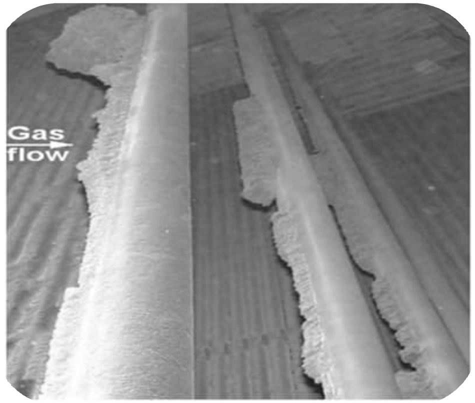
Boilers/Heat Exchangers



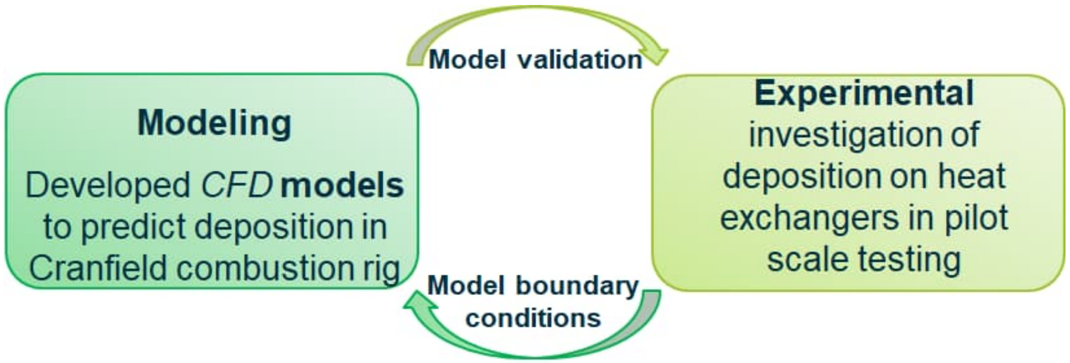
Deposition/corrosion around a heat exchanger tube

Fouling in heat exchangers



Deposit on real superheater tubes

Flow (particulate/liquid) or droplet impingement/ assisted erosion for Casings, Compressor components/ HRSG/ Boiler tubes/ Steam turbines/ Piping



Model efforts of interest for Power Plant Upgrades (e.g. Fuel flexibility)

Conclusions

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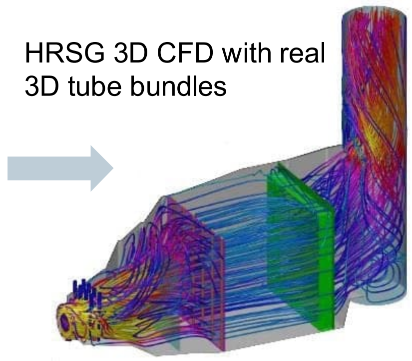
- Efforts are underway to develop component level simulation model to predict localized high-risk areas for mitigations
- Scale up and validation of fireside corrosion model to industrial systems, based on fundamental understanding of materials behavior and failure mechanisms
- The CFD/FE framework will enable simulations for varied fuel compositions and operating environments of Boiler/HRSG tubes for risk mitigations and operational flexibility
- CFD/FE framework for L0 stage/exhaust area established for steam turbines with accurate steam droplet velocity and size distribution at the turbine inlet to improve the erosion prediction
- Extend model to include the full final row of turbine stage in order to include more accurate water droplet transport models up into final turbine stage (Lagrangian particle tracking and wall impingement)

HRSG 3D model

HRSG 3D CFD with real 3D tube bundles



Steam turbine droplet
– exhaust recirculation