Probing Particle Impingement in Boilers with High-Performance CPUs & GPUs

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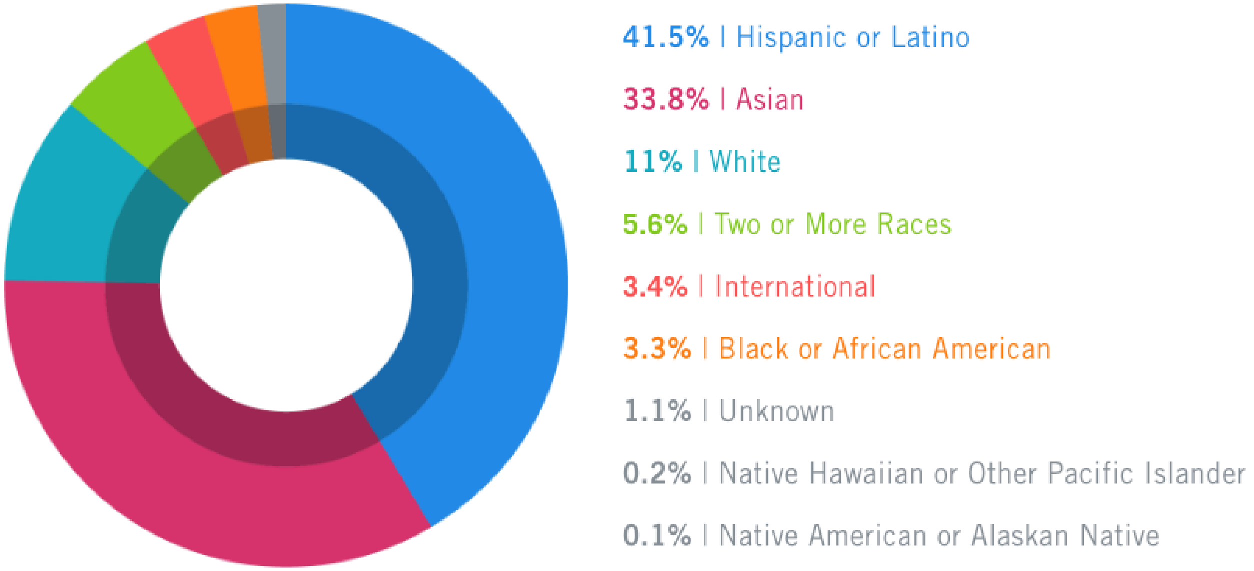
Outline

- Short introduction
- Why use Graphical Processing Units (GPUs) for particle impingement in boilers?
- Computational Fluid Dynamics (CFD) calculations with GPUs
- Particle-tracking calculations for computing erosion & accretion rates

HBCU-OMI Project at UC Riverside

- Official Hispanic Serving Institution
- Demographics:
- 57% first-generation students to attend college

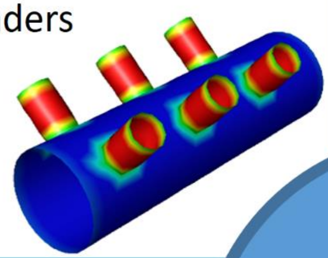


- Designated as *"top-performing institution for African American & Latino/a students"* by The Education Trust – **1 of only 3 institutions in the nation**

Research Expertise

- Deep focus & interest in *materials & high-performance computing*

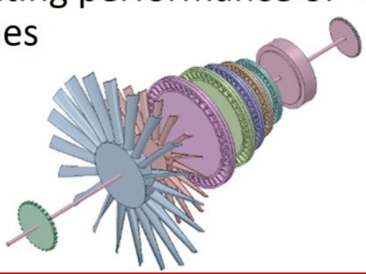
- **Research Thrust #1** – Predicting performance of boilers/headers



- **Efficiency & Speed** – Novel utilization of GPUs

High-Performance CFD Computing

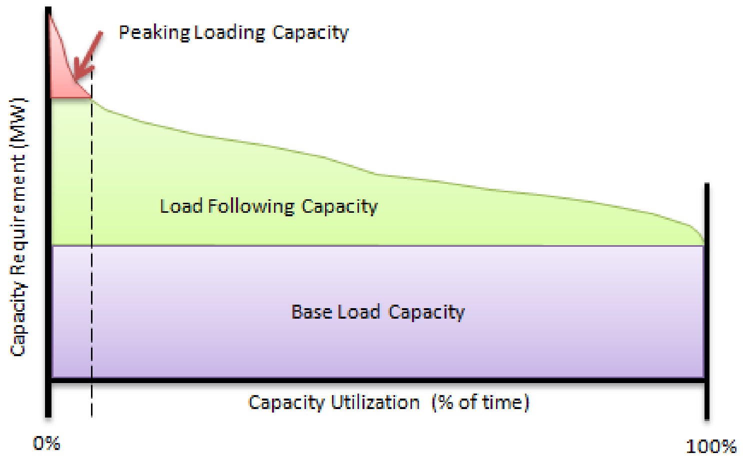
- **Research Thrust #2** – Predicting performance of turbines



- **Outreach** – Minority participation in NETL-relevant initiatives & state-of-the-art DOE computers

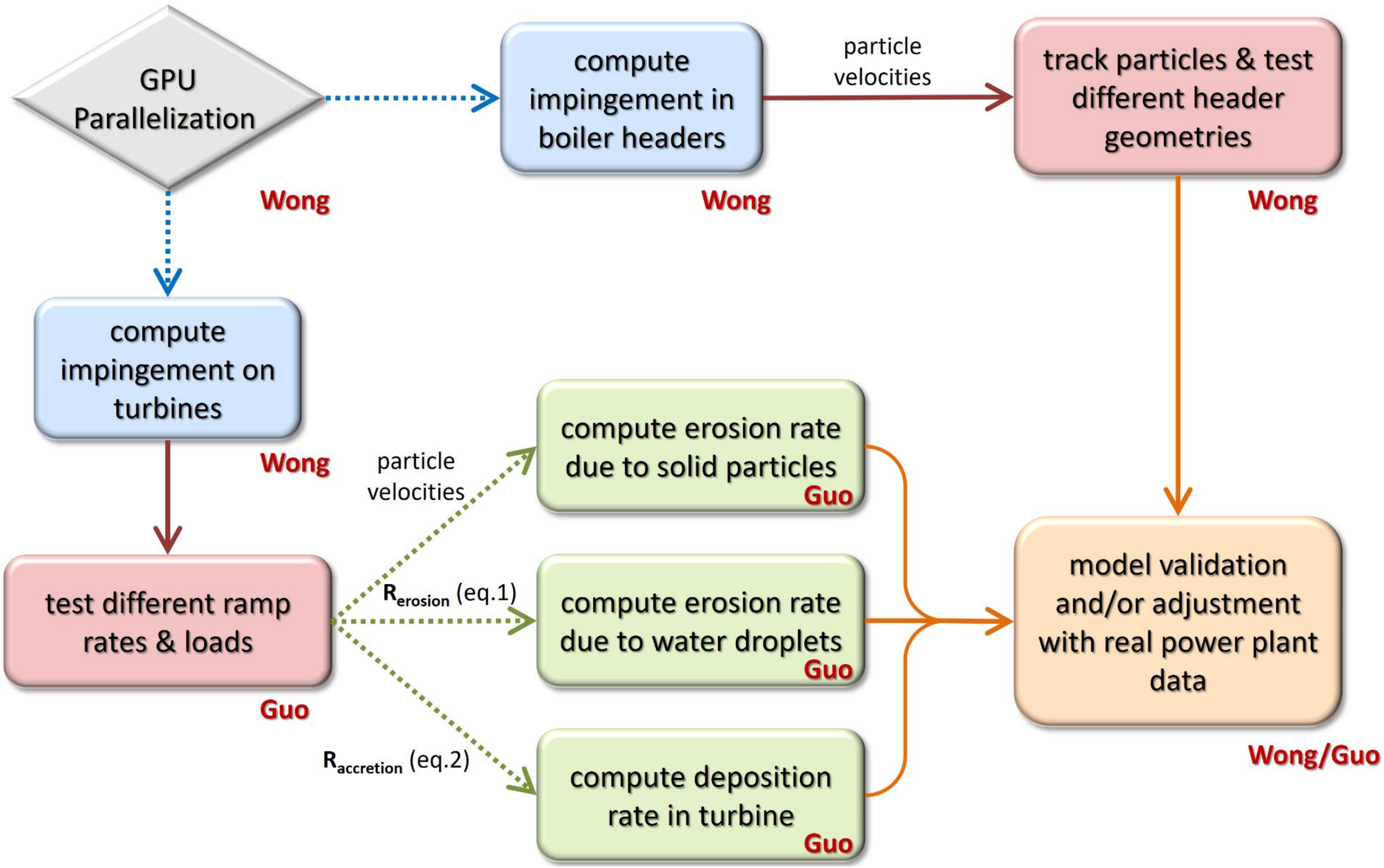
Background Information

- Coal-fired power plants have average life span of ~40 years
  - Originally designed for 30-year life & **baseline steady state operating mode**
- However, many plants currently operate in cycling & **load-following mode**
  - Plants not originally designed for such operations, leading to *lower efficiencies & faster material degradation*



- Identifying & diagnosing processes most impacted by cyclic operations is necessary for mitigating these inefficiencies

Task Summary & Project Timeline



Role of Computation

- Computation has several advantages compared to conventional physical/experimental diagnostics
  - Experiments are expensive & time-consuming
  - Nearly *limitless number of erosion processes & power-plant control variables*

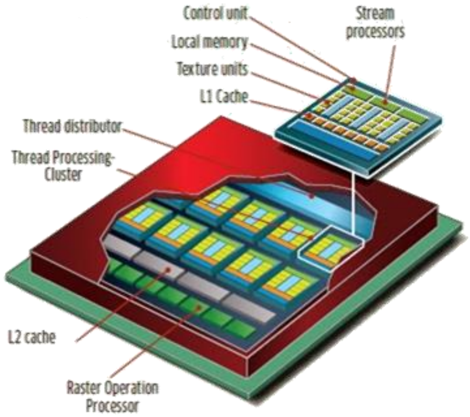
- Predictive computation
  - More cost-efficient
  - Leads to rational & more logical approach

- Use of Graphical Processing Units (GPUs) can further accelerate computational efficiency of calculations

Graphical Processing Units (GPUs)

- Computational Fluid Dynamics (CFD) calculations in Wong group carried out on *massively-parallelized GPUs*

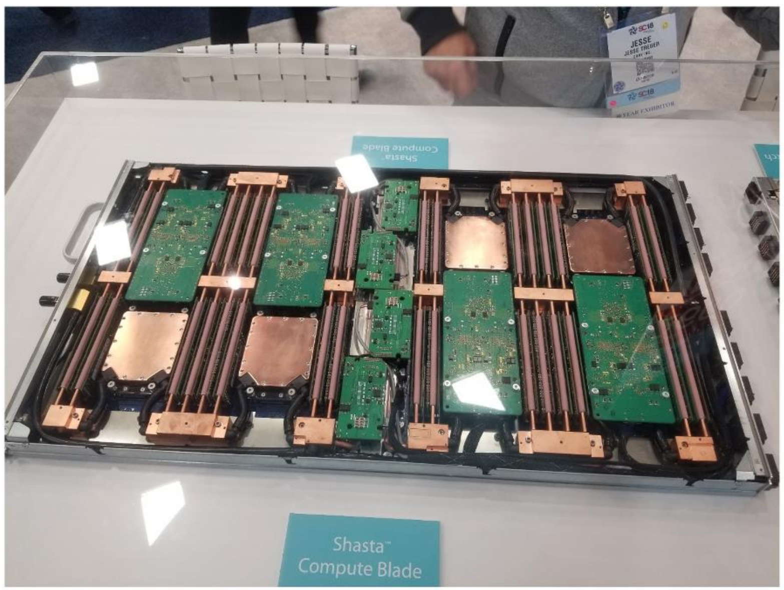
NVIDIA
GPU processors

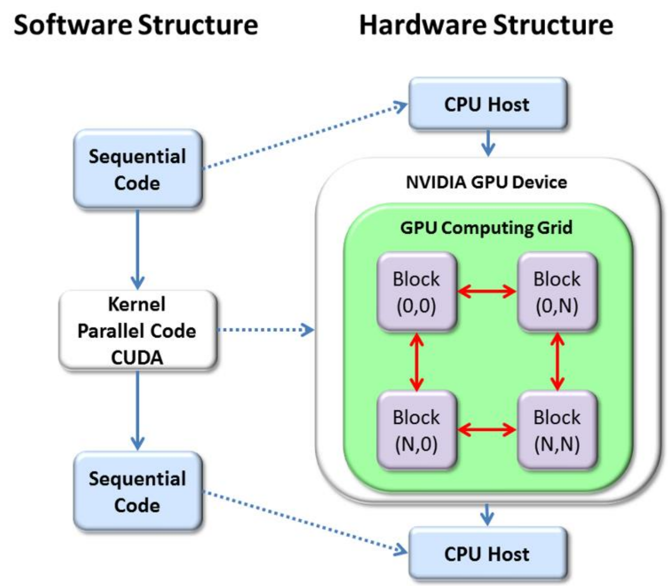


- Project utilizes ANSYS Fluent code with GPUs in PI's lab and DOE supercomputing facilities

How Do GPUs Work?

- GPUs comprised of thousands of computing threads that communicate with each other (red arrows) via shared memory





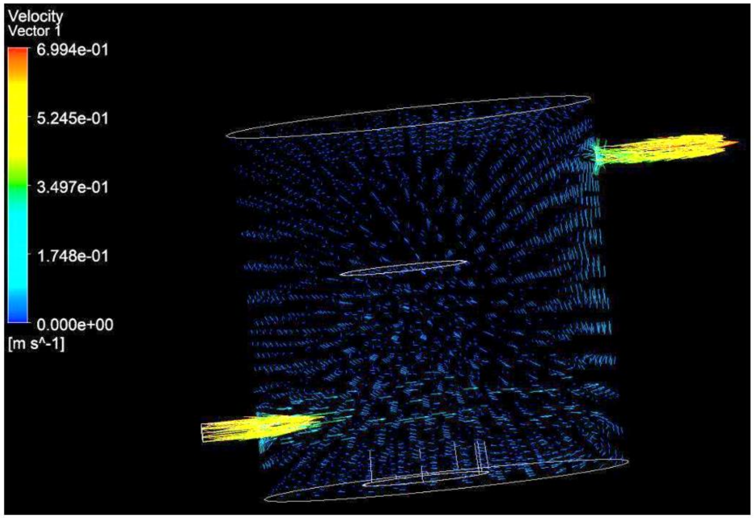
- Mesh points, particle positions, & velocity vectors from CFD calculations post-processed by CPU host

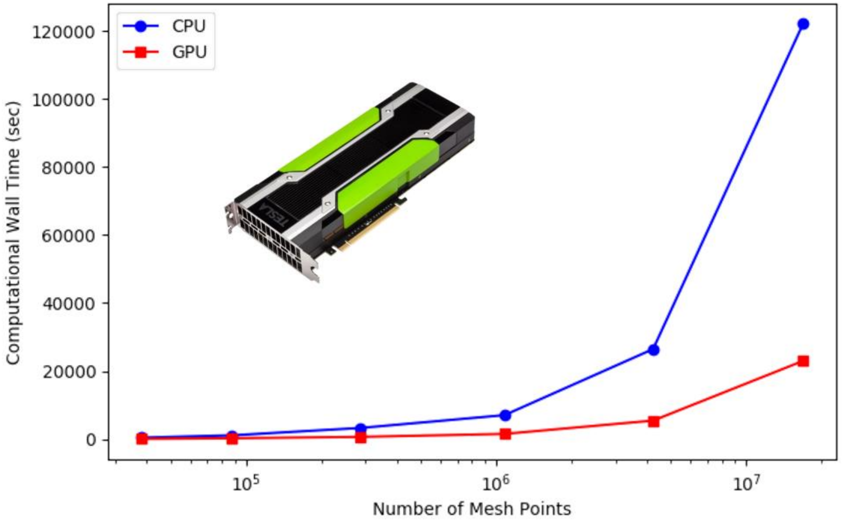
Hardware Support & Previous Results

- NVIDIA recently donated Titan V GPU to Prof. Wong for this project & other research

NVIDIA
Titan V GPU

- Recent Fluent benchmarks by Ms. Hyuna Kwon (Wong group)

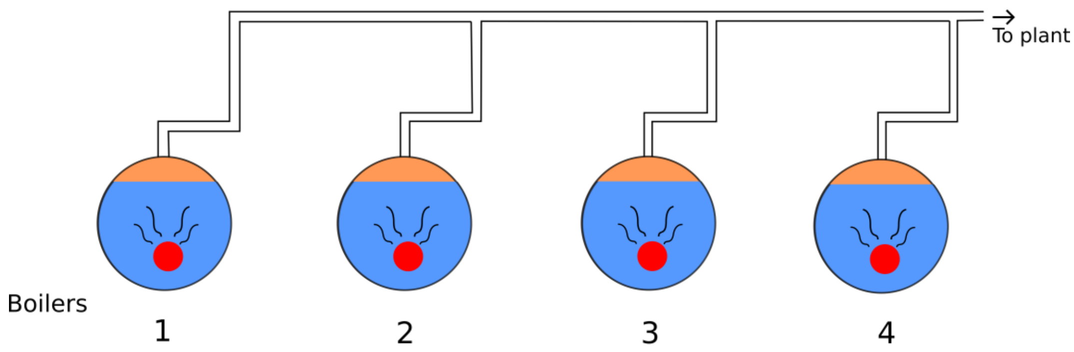


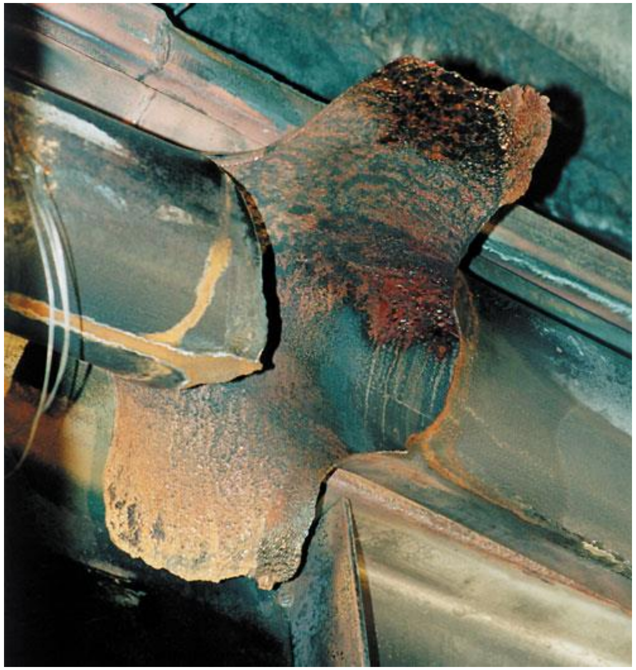


- *Significant computational savings for* ***large geometries***

Technical Background

- Erosion of machinery by high-speed particulates is ubiquitous in engineering processes
- Not easy to quantify all erosion mechanisms in one combined erosion prediction model (EPM)
- All particle motion characteristics can be monitored via coupled CFD-DPM/DEM
- Our study employs CFD-DPM and EPM to investigate erosion of boiler headers by solid-particle impact





https://www.babcock.com/resources/learning-center/finding-the-root-cause-of-boiler-tube-failure

- Schematic of boiler headers and example of erosive boiler header pipes

- Boiler header is a pipeline that transfers steam from boiler heads to plant

Boiler header

- Boiler header must operate in dust-rich environment
- Impact of high-speed solid particles causes serious erosion on boiler headers, preventing pipeline systems from operating safely
- Engineers have limited capabilities to prevent these effects during boiler header operation since erosion process is invisible
- We anticipate that CFD-DPM/DEM simulations combined with EPM can shed new light on complex erosion processes in boiler header

Governing equations

- Continuity equation (mass conservation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

- Euler's equation (momentum conservation)

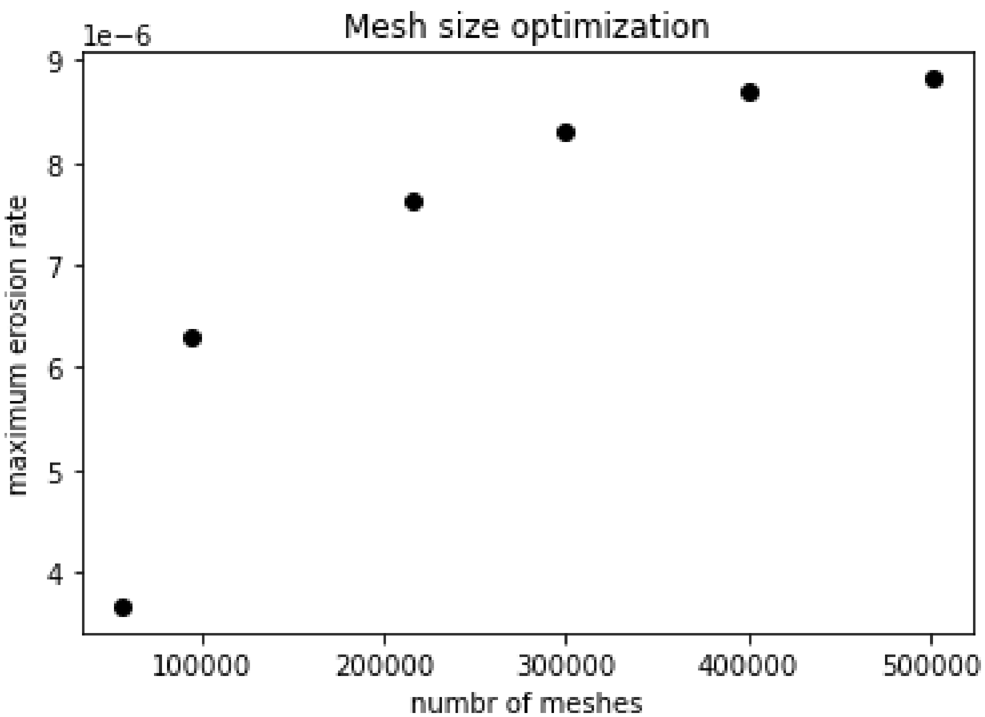
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \frac{\mathbf{F}}{\rho} - \frac{1}{\rho}\nabla p$$

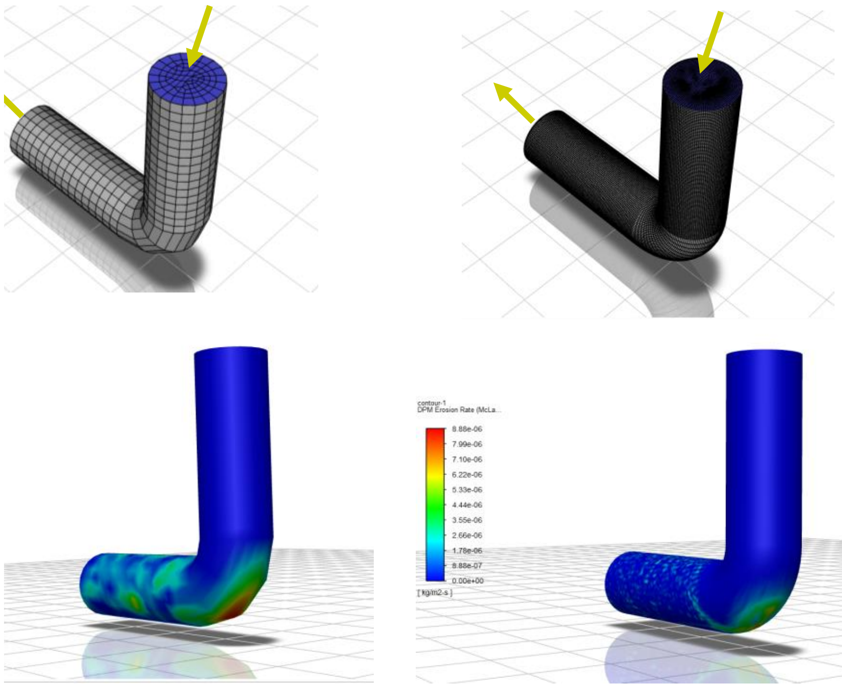
$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\underbrace{\mu \frac{\partial u_i}{\partial x_j}}_{\text{Viscosity}} - \rho \frac{\partial u_i}{\partial x_j} - \underbrace{\rho \overline{u_i' u_j'}}_{\text{Turbulence (k-}\varepsilon\text{ model)}}] + \underbrace{\rho g_i}_{\text{Gravity}} + F_i$$

Numerical details

- In this study, ICEM was used to generate tetrahedral meshes and a commercial solver (ANSYS FLUENT V.20.2) was used for all numerical simulations
- The pressure-based solver was applied, and the SIMPLE algorithm was used to correct the velocity and pressure.
- For the inlet of the calculation domain, a fixed fluid velocity was given and an 'out flow' was set on the outlet. For the fluid part, a no-slip boundary was set on the solid walls.

Optimizing mesh density





- Optimized mesh number = 500,000

Optimizing erosion model

- Erosion rate

$$ER = AF_S \nu_p^n f(\theta)$$

- A = material dependent coefficient
- F_S = particle shape constant
- f = function of impact angle

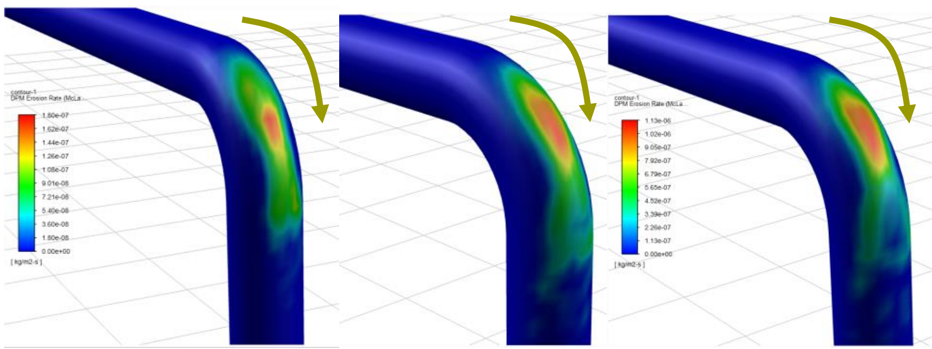
McLaury $$f(\theta) = \begin{cases} a\theta^2 + b\theta & \theta \leq \phi \\ xcos^2\theta sin(w\theta) + y^2 sin\theta + z & \theta > \phi \end{cases}$$

Finnie $$f(\theta) = \begin{cases} acos^2(\theta) & \theta \leq \phi \\ sin(w\theta) - xsin^2(\theta) & \theta > \phi \end{cases}$$

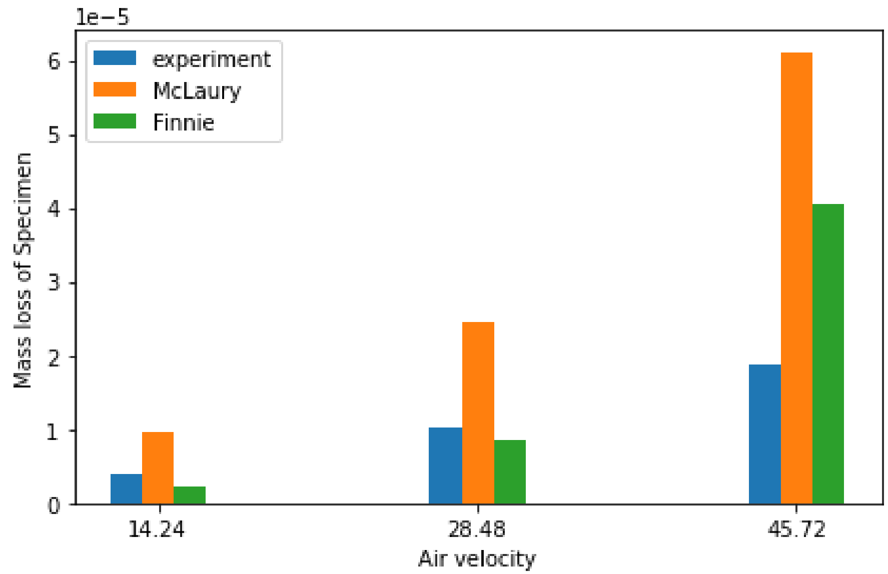
I. Finnie, “Erosion of Surfaces by Solid Particles.” WEAR, Vol. 3, pp. 87-103, 1960.

B. S. McLaury et al. "Modeling erosion in chokes". Proceeding of ASME Fluids Eng. Summer Meeting. San Diego, California. 1996.

Benchmark calculation



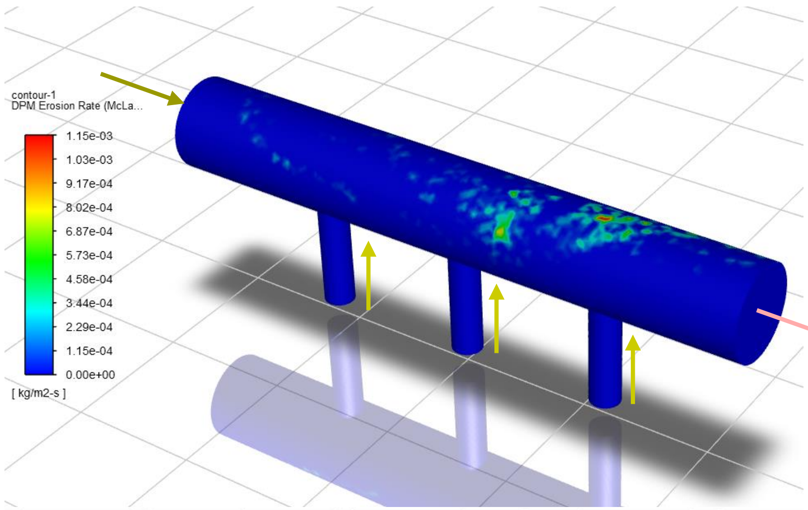
15.24 m/s 24.48 m/s 45.72 m/s

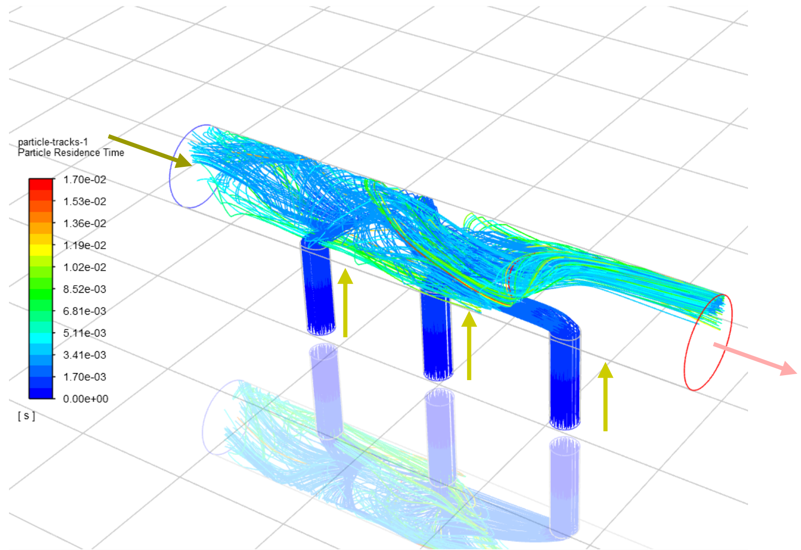


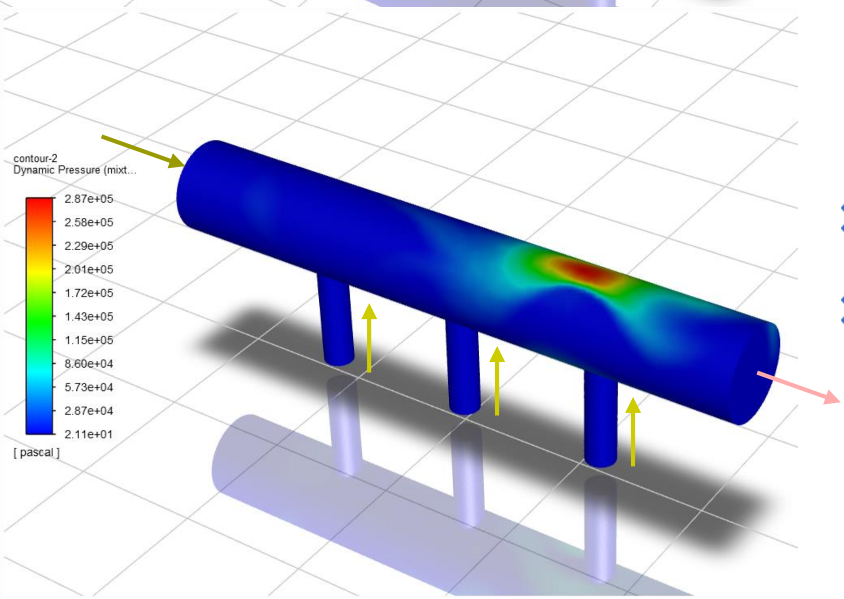
- Finnie model underestimates ER
- McLaury model overestimates ER
- Finnie model is more accurate, especially at high flow velocity

X. Chen, B.S. Mclaury, S.A. Shirazi, Application and experimental validation of a computational fluid dynamics (CFD)-based erosion prediction model in elbows and plugged tees, Comput. Fluids 33 (10) (2004) 1251–1272.

Test on simple boiler header design

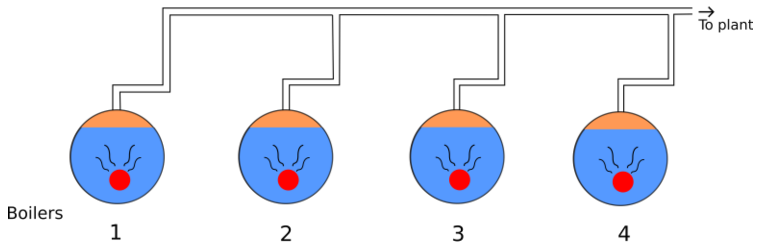




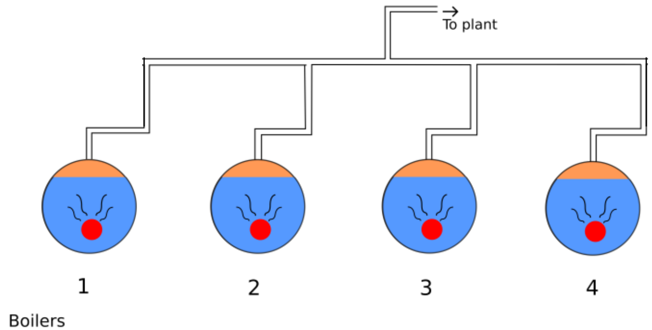


- Total erosion rate = 0.342 kg/m^{2}s
- Most erosion occurs near outlet due to high pressure

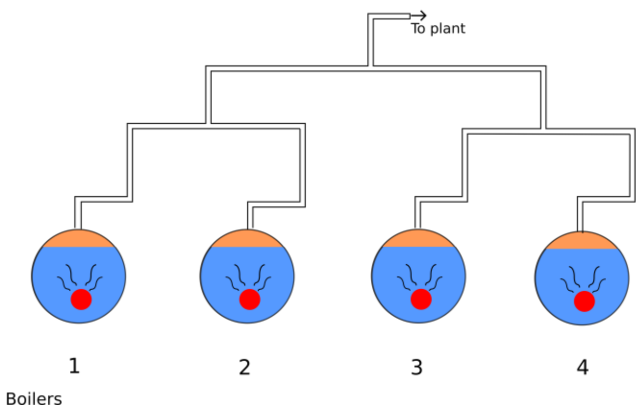
Optimizing design of boiler header



Serial design - Horizontal outlet

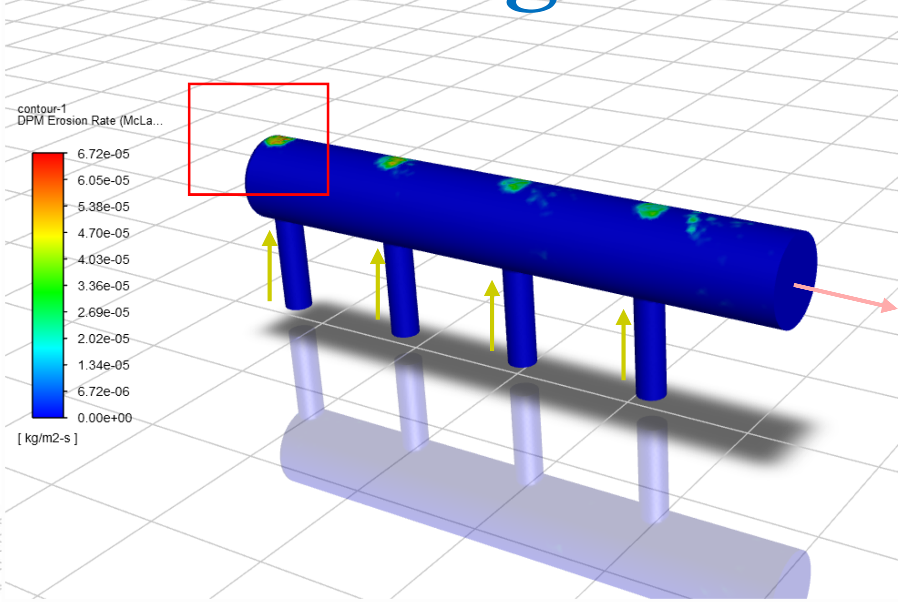


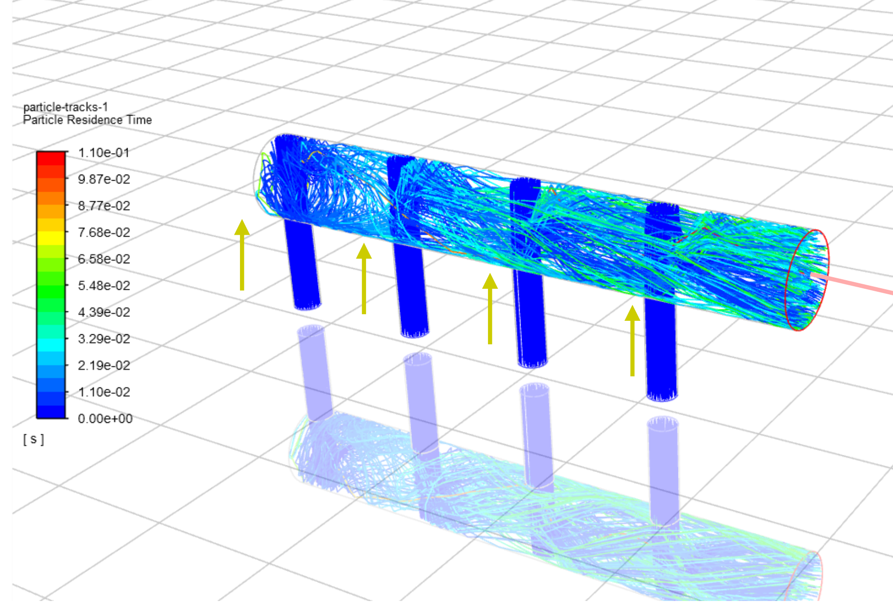
Serial design - Vertical outlet

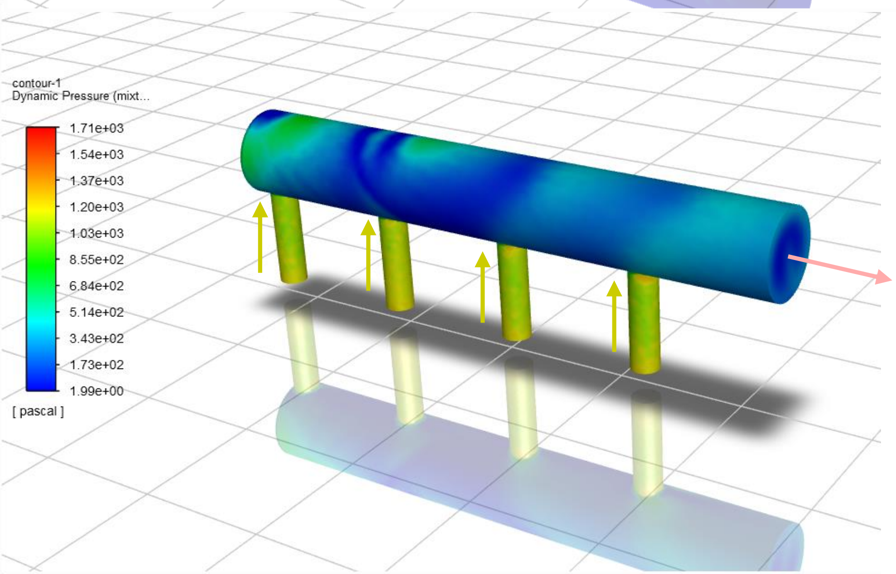


Parallel design - Vertical outlet

Serial design – horizontal outlet



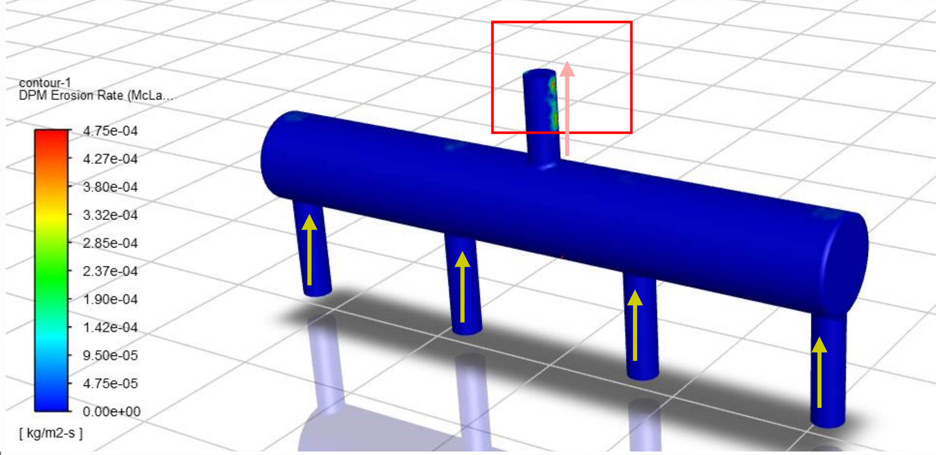


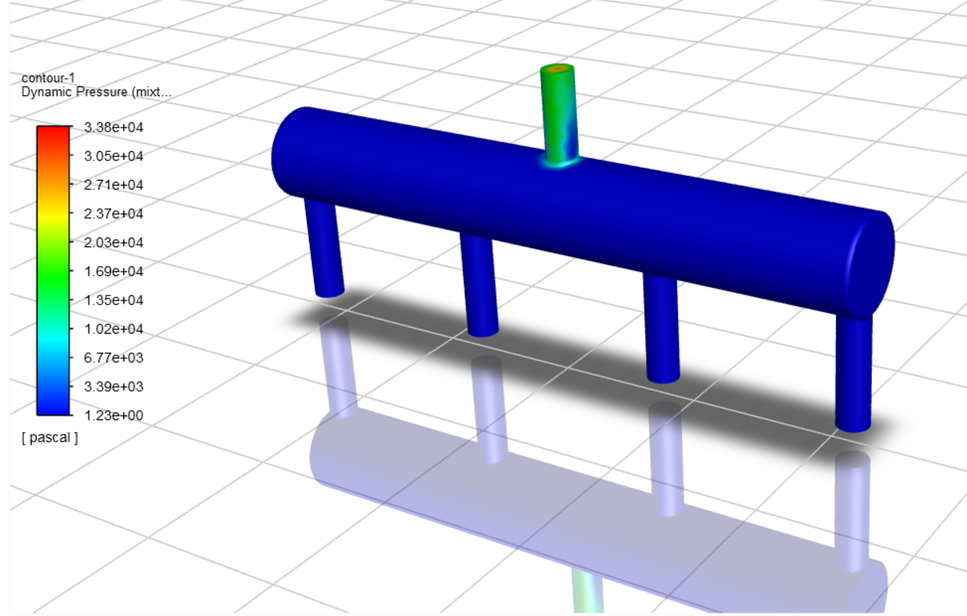


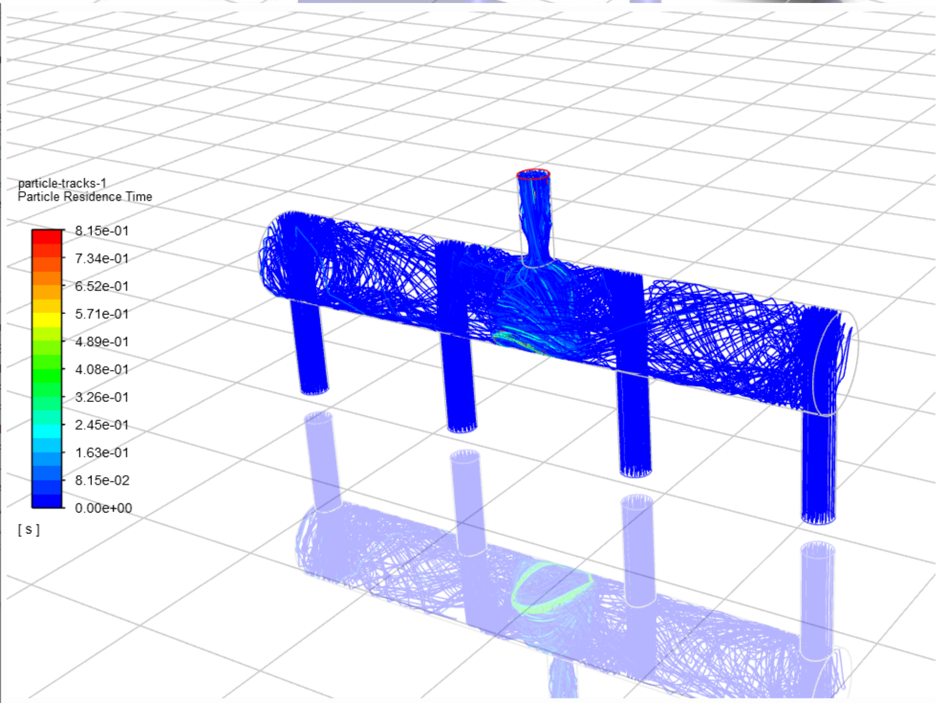
Max ER = 6.72×10^{-5} kg/m^2s

Total ER = 0.0228 kg/m2s

Serial design – vertical outlet



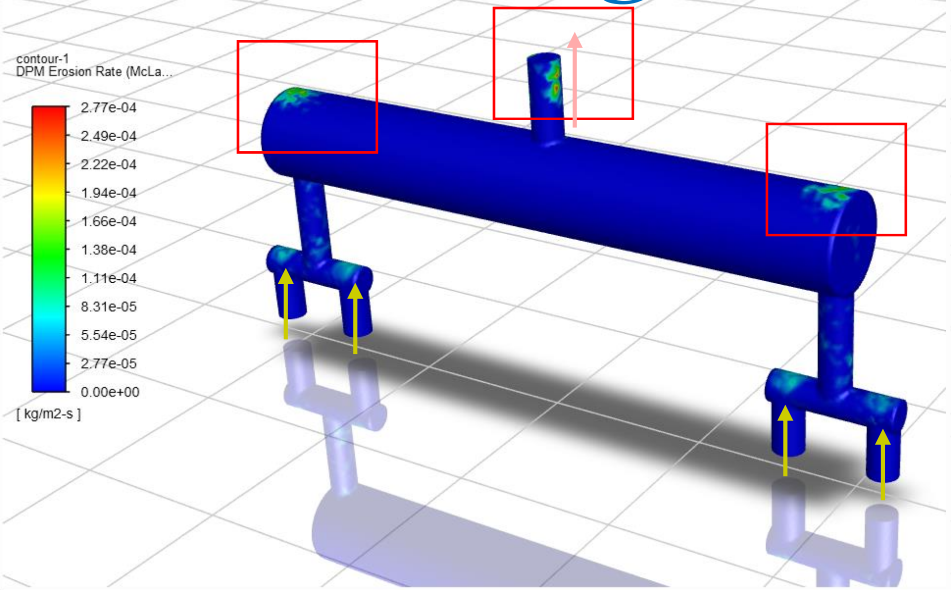


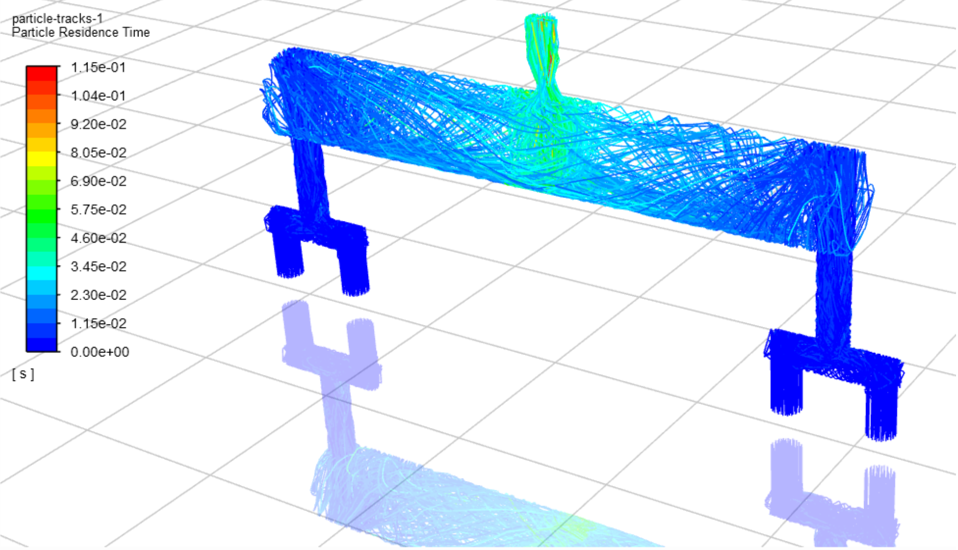


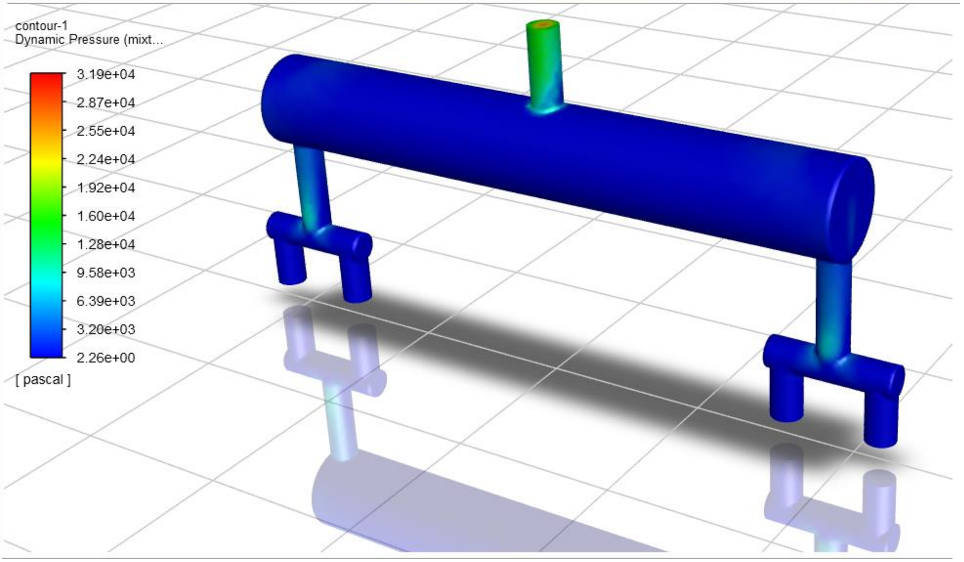
Max ER = 4.75 x 10^{-4} kg/m^2s

Total ER = 0.0511 kg/m^2s

Parallel design of boiler header







Max ER = 2.77×10^{-4} kg/m^{2}s

Total ER = 2.79×10^{-6} kg/m^{2}s

Optimizing header design

- Erosion-resistant designs of boiler header are vital
- In this study, ANSYS FLUENT V.20.2 was utilized to calculate erosion rate of boiler header
- McLaury equation predicts ER with best accuracy
- Boiler header with vertical outlet is more resistant
- Boiler header with parallel tube alignment is more resistant
- Erosion occurs at high pressure area (near outlet)

Future plans

- Optimize number of branched pipes (row and column)
- Optimize angle between main pipe and tubes
- Optimize erosion rate equation

Thank you!

- Special thanks to NVIDIA (GPUs)
- Supported by UCR/HBCU DE-FE0031746