Environmental Validation of Materials and Design Concepts to Enable Operational Flexibility of Existing Coal Power Plants

Anand Kulkarni, Siemens Corporation

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Acknowledgements

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Outline

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- Technology Maturation Plan

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Project information

PI: Anand Kulkarni

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

Strategic Partner: Siemens Gas and Power, Oak Ridge Natl Lab, Cranfield Uni.

Total Project Funding: $2.5M ($2M Federal/$500K Cost Share)

Project Objectives

1. Topology optimization to redesign tubes, via additive manufacturing (AM), with multi- functionality to address creep-fatigue, steam oxidation on the inside and fireside corrosion on the outside for insights into performance improvements and time-consuming repairs.
2. Environmental relevant testing of conventional (tube, welds) and redesigned components to handle load changes, low load and/or cycling conditions for damage impact for input into techno-economic analysis to compare with conventional ASME Code approved materials/ manufacturing processes.
3. Testing of technologies to improve plant efficiency including a) advanced topping cycles, and b) novel heat recovery schemes utilizing molten salt integration with absorption chillers.

Meet FOA Guidelines

Power Plant Component Improvement	
Funding Opportunity Objective	**Objective of Proposed Program**
Environmental testing of technologies for flexibility and efficiency ⇨	Relevant testing of design and operating parameters (load changes, low load and/or cycling conditions and advanced topping cycles) in small-scale (~100 kWth) pilot plant at Cranfield University
Testing of techniques which shorten the length of time-consuming repairs ⇨	Additive manufacturing enables fast design-manufacturing iterations to produce near-net shapes, significantly reducing lead-time up to 50% from current baseline
Power plant component improvements ⇨	Topology optimization for boiler/HRSG tubes with multi-functionality to address creep/fatigue for cyclic operations, steam oxidation on the inside and fireside corrosion on the outside
Testing of thermal management (energy storage) technologies ⇨	Integration schemes for the turbine exhaust (low temperature heat source) to be cooled efficiently via nocturnal heat storage (eg. water) taking the advantage of drop in night time temperature. Or Li/Br based absorption chiller systems driven by thermal energy and waste heat.

- Demonstration of multiple approaches for increased efficiency/reliability of coal power plant on pilot test rigs at Cranfield University (UK).
- Demonstrate improved materials capability vs baseline for wide range of operations for existing power plants.

Project Team and Expertise

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Anand Kulkarni, Siemens
Principal Investigator

Materials knowledge, Operational flexibility, AM process chain
Anand Kulkarni, Siemens
Kyle Stoodt, Siemens
- Design and analysis
- Materials systems
- AM process-structure-property linkages

Pilot rig testing, thermal management and data analytics
Nigel Simms, Cranfield University
Kumar Patchigolla, Cranfield University
- Pilot rig testing and data analytics
- Heat recovery for thermal power plants
- Materials systems

Data driven AM component manufacturing
Mike Kirka, ORNL/MDF
Sebastien Dryepondt, ORNL
Sudarsanam Suresh Babu, ORNL
- Topology optimization
- AM buildup trials

Contract Administration
Keryl Cosenzo, Siemens
- Contract management

Financial Management
Terri Held, Siemens
- Financials, invoicing
- Subcontractor agreements

Senior Technical Advisors
Robert Pierson, Riley Power
Brian Vitalis, Riley Power
- Component design and conditions
- Input for pilot rig testing

Program Management
Sudhir Rajagopalan, Siemens
- Risk analysis
- Program management

Team Member	Skill and expertise
Principal Investigator: Anand Kulkarni	Senior Key Expert; 25 years in research and technology in the area of materials/coatings for power systems, 10 years in materials needs for fuel-flexible environments, 5 years in data driven additive manufacturing (AM) of components
Siemens Team: Kyle Stoodt (KS) Sudhir Rajagopalan (SR)	**KS**: Senior Engineer; 8 years expertise in materials joining, advanced machining and additive manufacturing **SR**: Senior Scientist, Program Manager; 20 years in research of steels for gas and steam turbines
Cranfield Team: Nigel Simms (NS) Joy Sumner (JS) Kumar Patchigolla (KP)	**NS:** Professor; 30 years' experience of power generation systems, Development of advanced higher efficiency and lower emission thermal power systems, Performance of components in conventional and advanced power systems. **JS:** Senior Lecturer, Expert in degradation of materials in coal and gas-fired power plants **KP:** Senior Lecturer, Expert in heat recovery and water use systems for renewable and thermal power plants
ORNL Team: Sebastien Dryepondt (SD) Michael Kirka (MK) Patrick Geoghegan	**SD**: Materials expert; High temperature materials and Corrosion, 8 years' experience for Materials/AM applications for CHP **MK**: AM Expert; 10 years' experience on fabrication by AM of high temperature structural components **PG**: AM Expert; 10 years' experience in AM design and topology optimization

The technical team is strong and has been working together for 15+ years

Tube Experiences in Existing Coal Power Plants with Operational Flexibility

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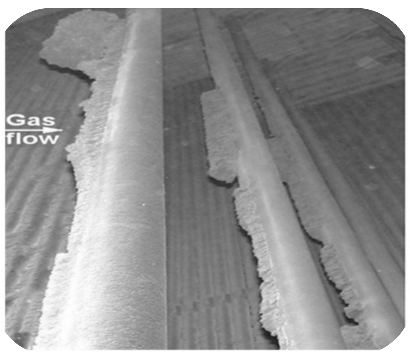
LP Superheater/Evaporator Tubes

LP Condensate Preheater Tubes

Fouling in heat exchangers



Deposit on real superheater tubes

Corrosion fatigue damage in the steam-cooled wall where cycling caused differential thermal growth

Waterwall corrosion fatigue damage due to cycling damage at a corner

Reheater outlet header and tube-to-header weld fatigue damage as a result of thermal loading and deflection during startup cycles.

HRSG feedwater heater tube leaked from cold-end corrosion during cycling.

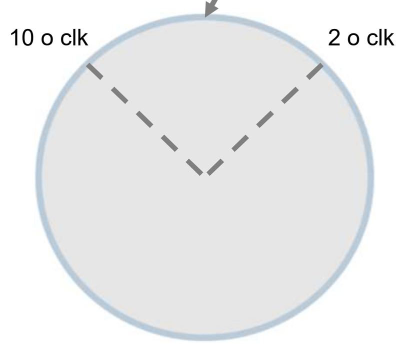
Courtesy: Intertek-Aptech

Tubes related failures observed in cyclic operations

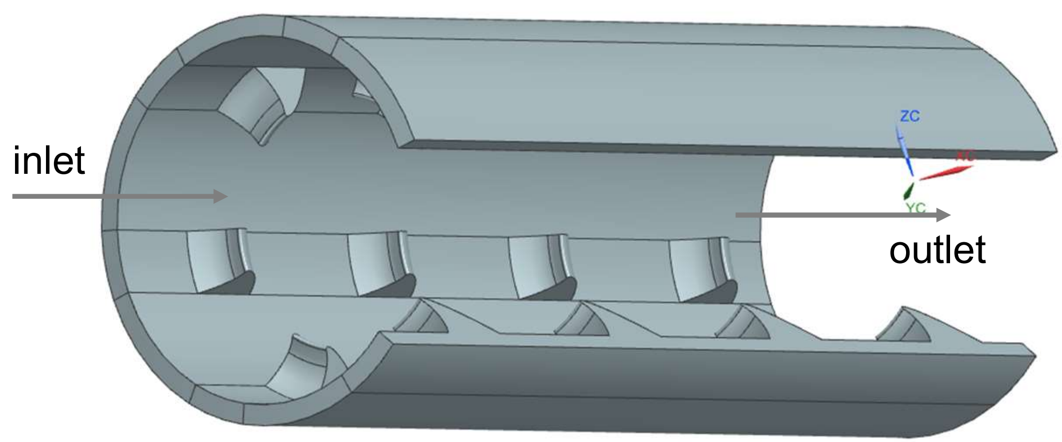
Developments focus particularly on generic boilers and heat exchangers in coal-fired power plants since boiler tube failures continue to be major cause of forced outages and statistically account for 6% of availability loss

Task 2.0: Data Driven AM Design and Component Manufacture

- Single phase flow: High pressure steam inside the tube
- High pressure steam causes high hoop stresses and eventually leads to high creep
- Thermal fatigue is caused only due the intermittent operation of the plant. Intermittent operation of the plant causes change in temperature of the steam inside the tube.



Exposed to high ash deposition causing corrosion ; local thickening will help to improve the creep capability



- Need to have surface features without tips
- So how about an internal surface profile that is more undulating? (like a golf ball surface?)

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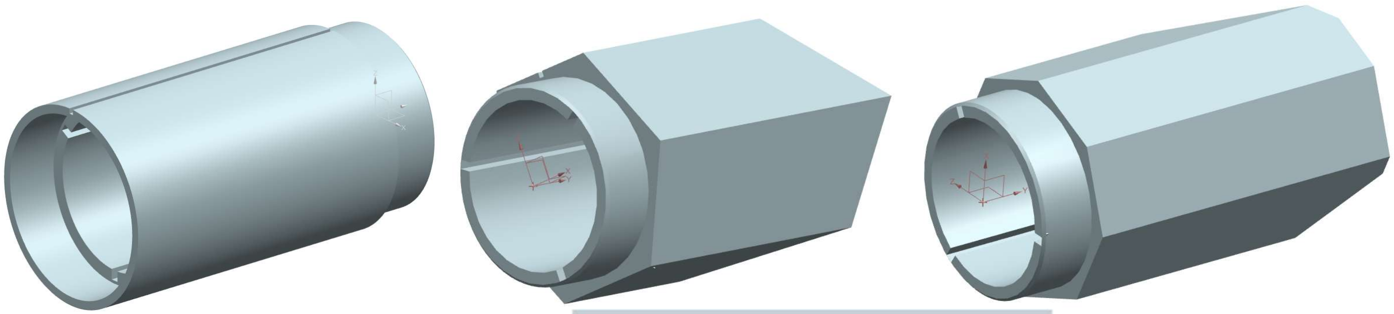
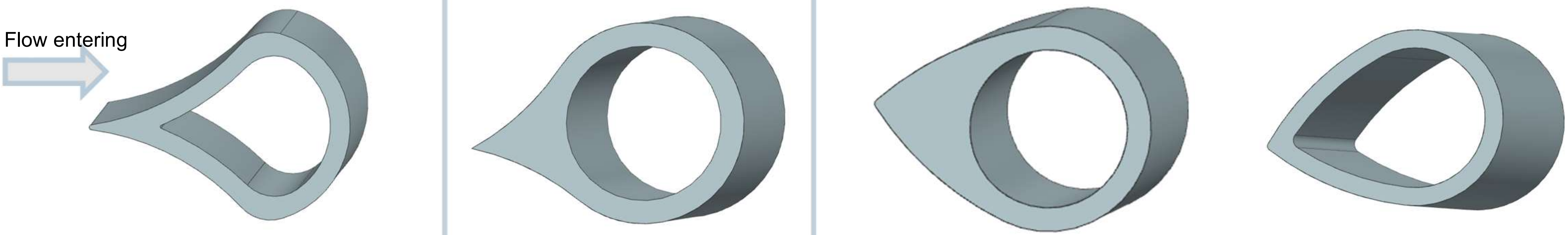
Test Sample Geometry for Topology Optimization for functional Optimization



- Since, Deposition flux α sin(γ)
- Smaller impact angle -> smaller deposition flux
- Conical front or a tear-drop shaped front will leads to gradual decrease of impact angle



Tear-drop shape with a concave profile and non-circular ID

Tear-drop shape with a concave profile and circular ID

Tear-drop shape with a convex profile and circular ID

Tear-drop shape with a convex profile and non-circular ID

MPTO Application to Boiler Tube Anti-fouling & Increasing Heat Exchanger Efficiency – ***Problem set up***

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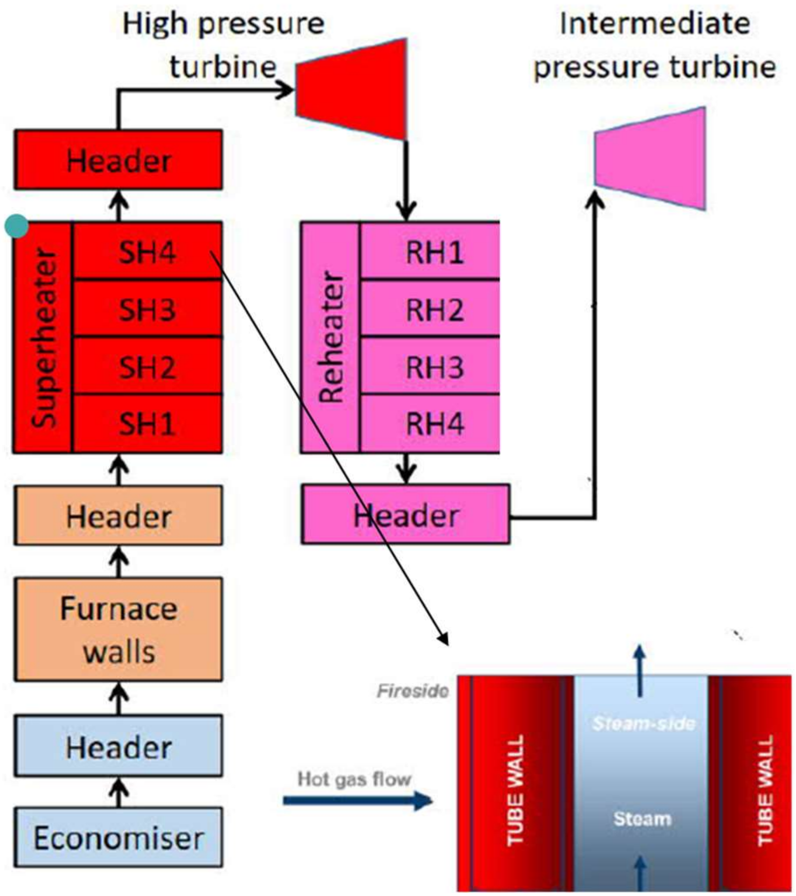
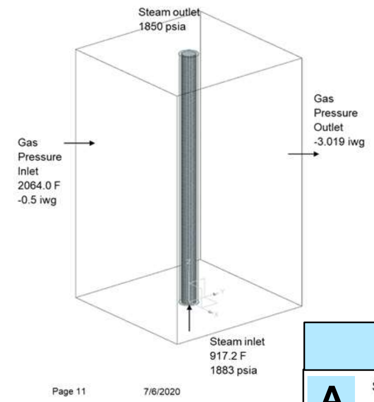
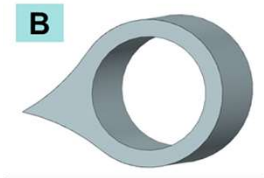


Multiphysics Topology Optimization (MPTO) application to optimize external surface, combined with design of experiments for internal surface features



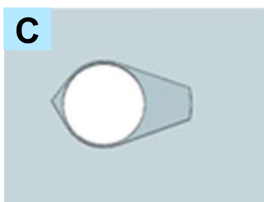
External surface features

B



(from UTK)

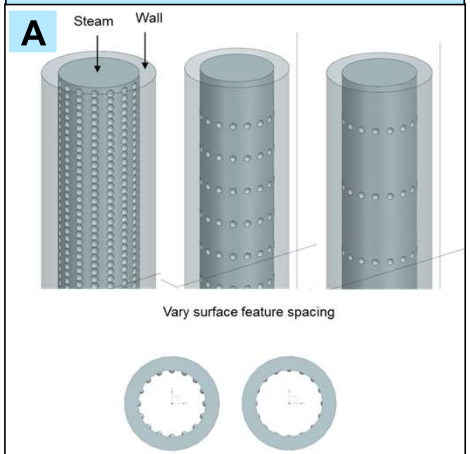
C



NEW! Thermal flow topology optimized (see next slide)

Internal surface features

A



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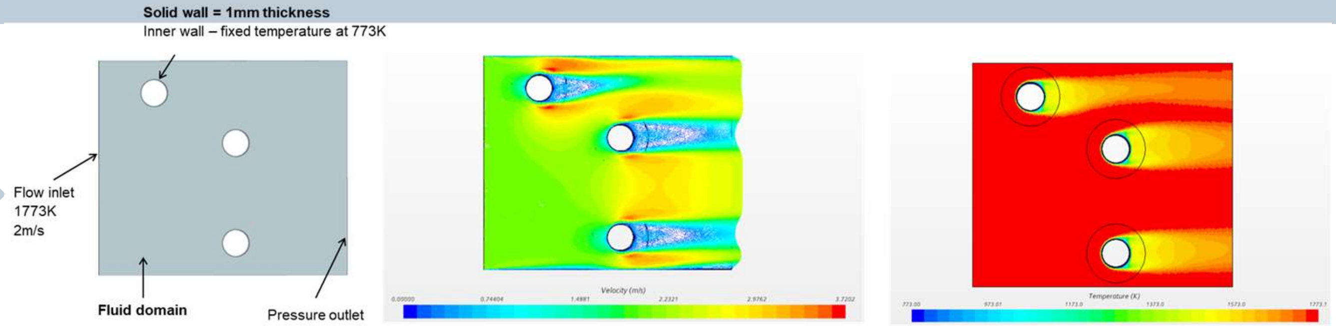
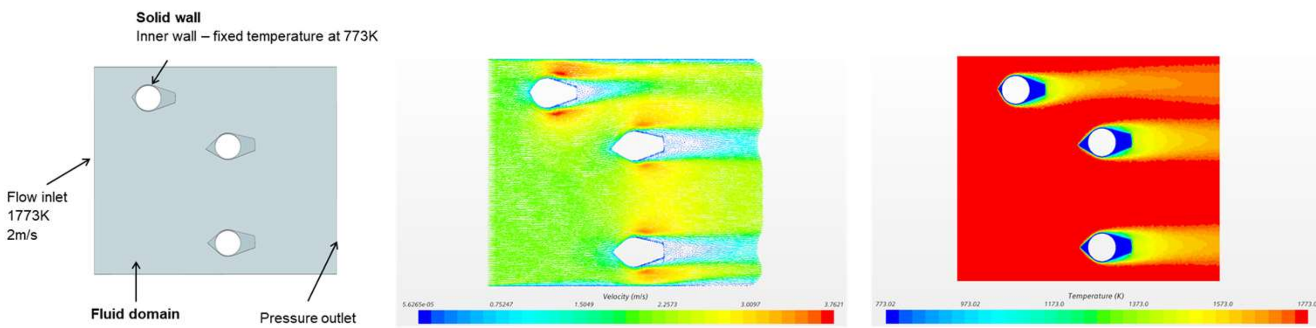
MPTO for EXTERNAL Surface Optimization - Results

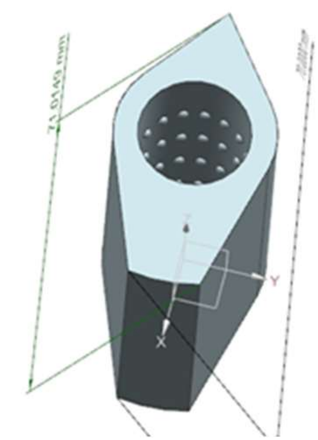
BASELINE DESIGN



- **Conjugate heat transfer analysis in STAR-CCM+**
- Pressure drop from inlet to oulet= 0.221 Pa
- Mass flow averaged temperature at outlet = 1732 K

TOPOLOGY OPTIMIZED DESIGN





- **Conjugate heat transfer analysis in STAR-CCM+**
- Pressure drop = 0.175 Pa
- Mass flow averaged temperature at outlet = 1727 K → *Compared to 1732 K for baseline design*

AM Printed Geometries – LPBF IN625 in EOS M290-1

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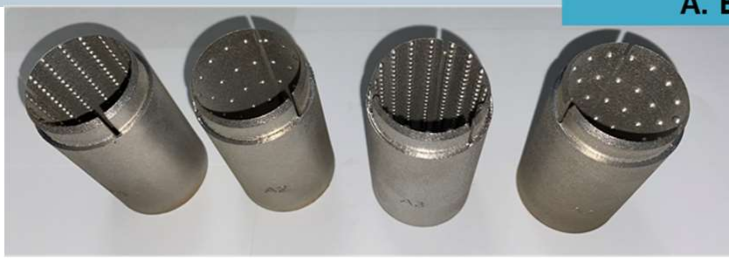
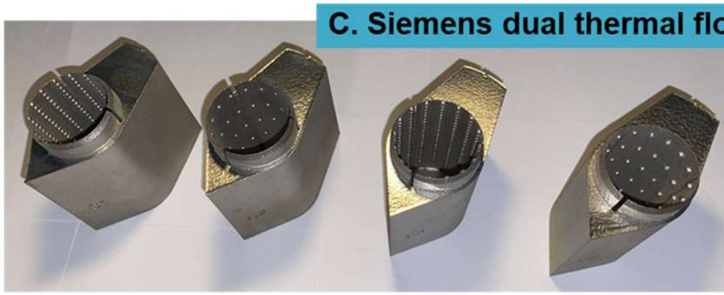
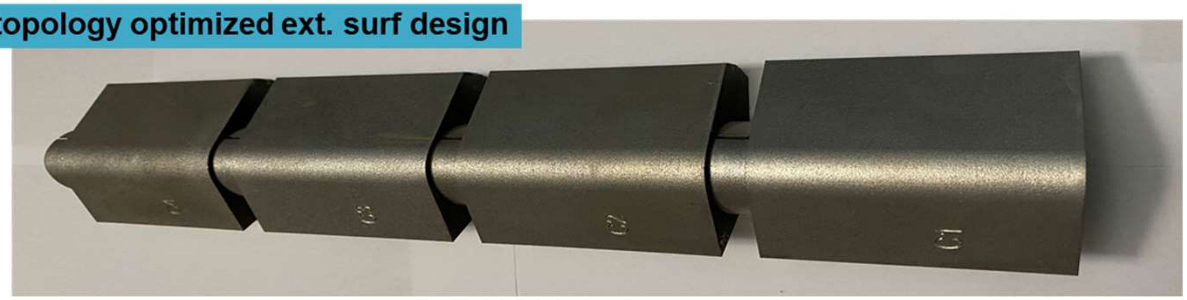
A. Baseline cylinder



B. UTK ext. surf design

C. Siemens dual thermal flow topology optimized ext. surf design





Samples currently at Cranfield

Task 3.0 – Pilot Scale Component trials

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Operation of pilot scale combustion plants

Subtask will focus on using pilot test rigs to expose small-scale components in specific operating environments targeted at the simulation of those anticipated for flexible operating conditions.

Two pilot scale test rigs will be used to target particular operating environments/conditions:

- one to investigate fireside issues
- one for steam-side issues.

By separating fireside and steam-side environmental exposures, it will be possible to simplify the trial component designs and provide mitigation options, e.g.:

- by control of exposure conditions to investigate the effects of specific exposure parameters (e.g. cycling environments/temperatures on fireside)
- by only applying external coatings on components for fireside tests and internal coatings on components for steam tests.

Subtask 3.1 – Operation of pilot scale combustion plants
A) Pulverized coal pilot scale combustion test update

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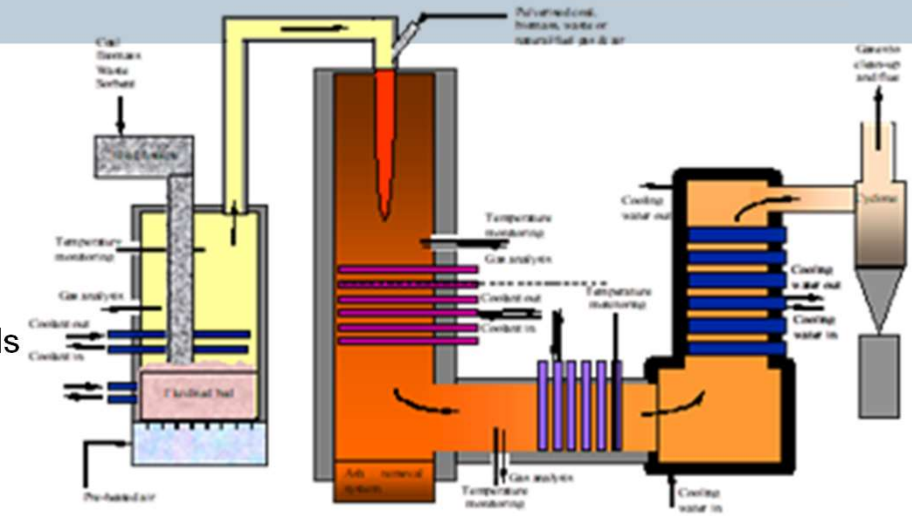

Test runs:
- Cyclic: Coal during day (8 h); natural gas overnight (16 h)
- baseline

Combustion of pulverised coal - discussions about potential supply of a high S US coal with EDF Energy (from West Burton power station)

Series of cooled probes to be exposed hot combustion gas stream (details on next slide):
- 12 probe locations with three different target surface temperature ranges and two exposure time
- AM, welded and conventional materials

Pilot scale research facility:
- logging of operational and exposure parameters, e.g.: gas / component temperatures; gas pressures; flue gas compositions.
- combusted flue gas environment can be varied and controlled - e.g. by changing fuels, flue gas temperature, air/fuel ratio - to generate specific exposure conditions.

Component Exposures

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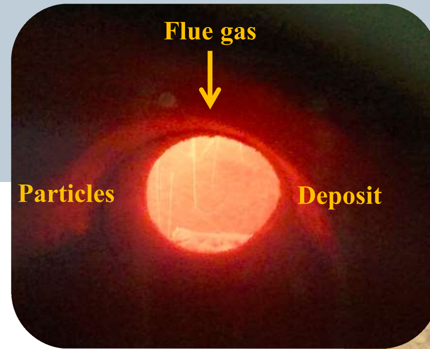

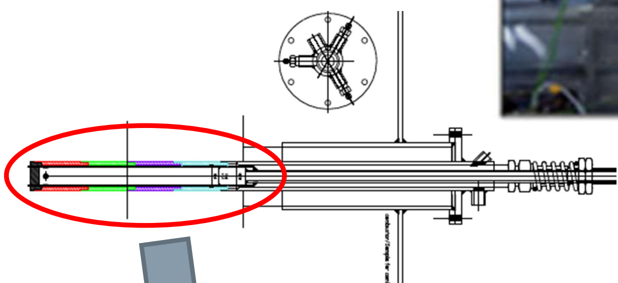

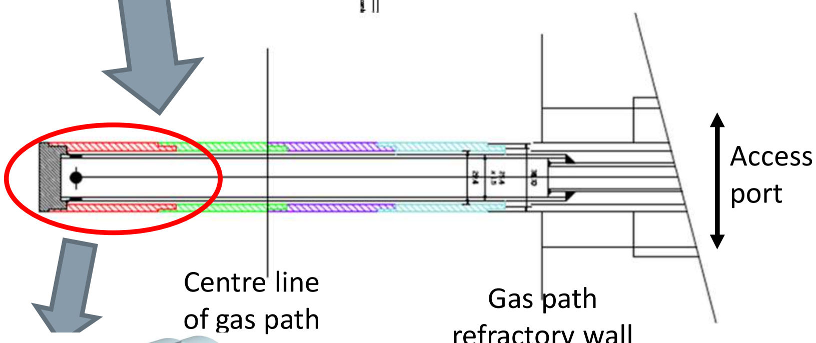

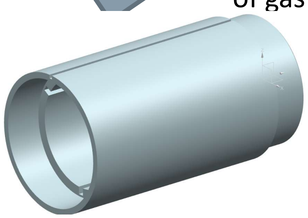

Probe location	Probe number	Sample position				Target metal temp range (°C)	Exposure time (h)
		1	2	3	4		
1	1	AM#	AM#	AM#	AM#	560-620	1000
2	2	Weld#	Weld#	Weld#	Weld#	560-620	1000
3	3	T22	T23	T91	T92	560-620	1000
4	4	347HFG	304	310	HR3C	560-620	1000
5	5A	T22	T23	T91	T92	560-620	500
	5B	347HFG	304	310	HR3C	560-620	500
6	6A	AM#	AM#	AM#	AM#	560-620	500
	6B	AM#	AM#	AM#	AM#	530-590	500
7	7	AM#	AM#	AM#	AM#	530-590	1000
8	8	T22	T23	T91	T92	530-590	1000
9	9	347HFG	304	310	HR3C	530-590	1000
10	10A	T22	T23	T91	T92	530-590	500
	10B	347	304	310	HR3C	530-590	500
11	11	T22	T23	T91	T92	500-560	1000
12	12	347HFG	304	310	HR3C	500-560	1000

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Subtask 3.1 – Operation of pilot scale combustion plants
B) Steam oxidation test facility

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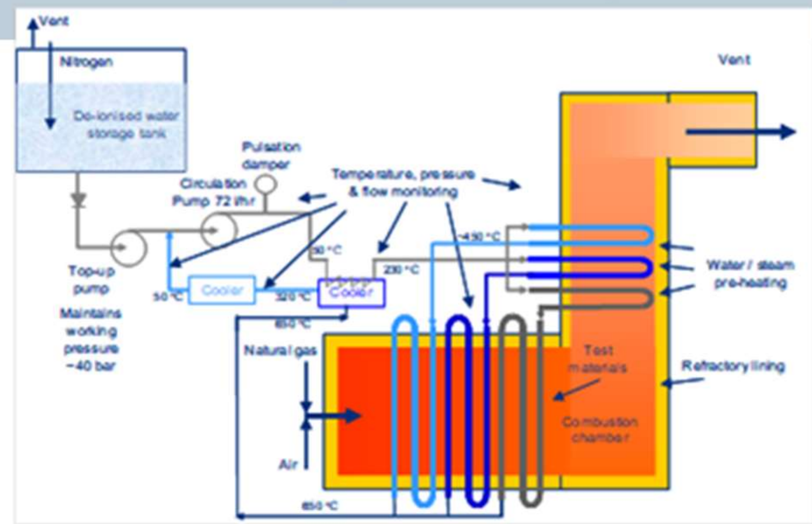
This rig exposes steam/water cooled components in hot flue gases generated by natural gas / air combustion.
The components are in the form of 1 m long tubes (with flanges welded at each end).
Components connected in series of three in 2 test loops that operate in parallel. Each can be manufactured from a different material and internal coatings applied if required.
Metal/steam temperatures set by the combustion air temperature and the steam/water flow rates.
Rig operation/exposure conditions are monitored by a data logging system.



Steam tube exposure facility

Heat exchanger tubes during inspection in test facility

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Task 3.1(B) Component Exposures and Operating Conditions for Tests

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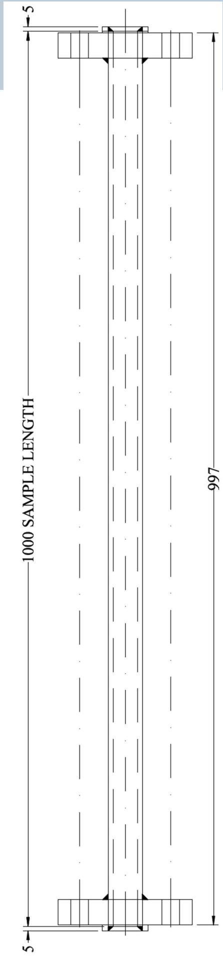
Components in the form of 1 m long flanged tubes
- Tubes cross the hot combusted gas path
- Tubes form part of steam circuit (~40 barg)
  - Tubes must satisfy insurance requirements for pressure vessels
- As joints are flanged, each tube can be:
  - Manufactured from different materials
  - Changed during intermediate rig shut-downs

Tubes arranged in parallel steam paths
- 3 tubes in each steam path
- Steam heats up as it passes through tubes

Operational flexibility – to be discussed and agreed
- Cyclic exposure vs baseline (2 test series)
  - Exposure times – 1000 h, 2000 h?
- Cycling combusted gas temperatures
  - High/low (not on/off to avoid steam condensation issues)
- Inside tube metal temperatures - ~500 – 600 °C (increasing along each steam path)
  - T22, T91, 347HFG, HR3C
  - additive manufacture ?
  - Alternative shapes ?



Tube example:
- length = 1 m
- Outside diameter = ~38 mm
- Inside diameter = ~28-30 mm

Revised Plan for PF Combustor and Steam Rig Operations (Task 3)

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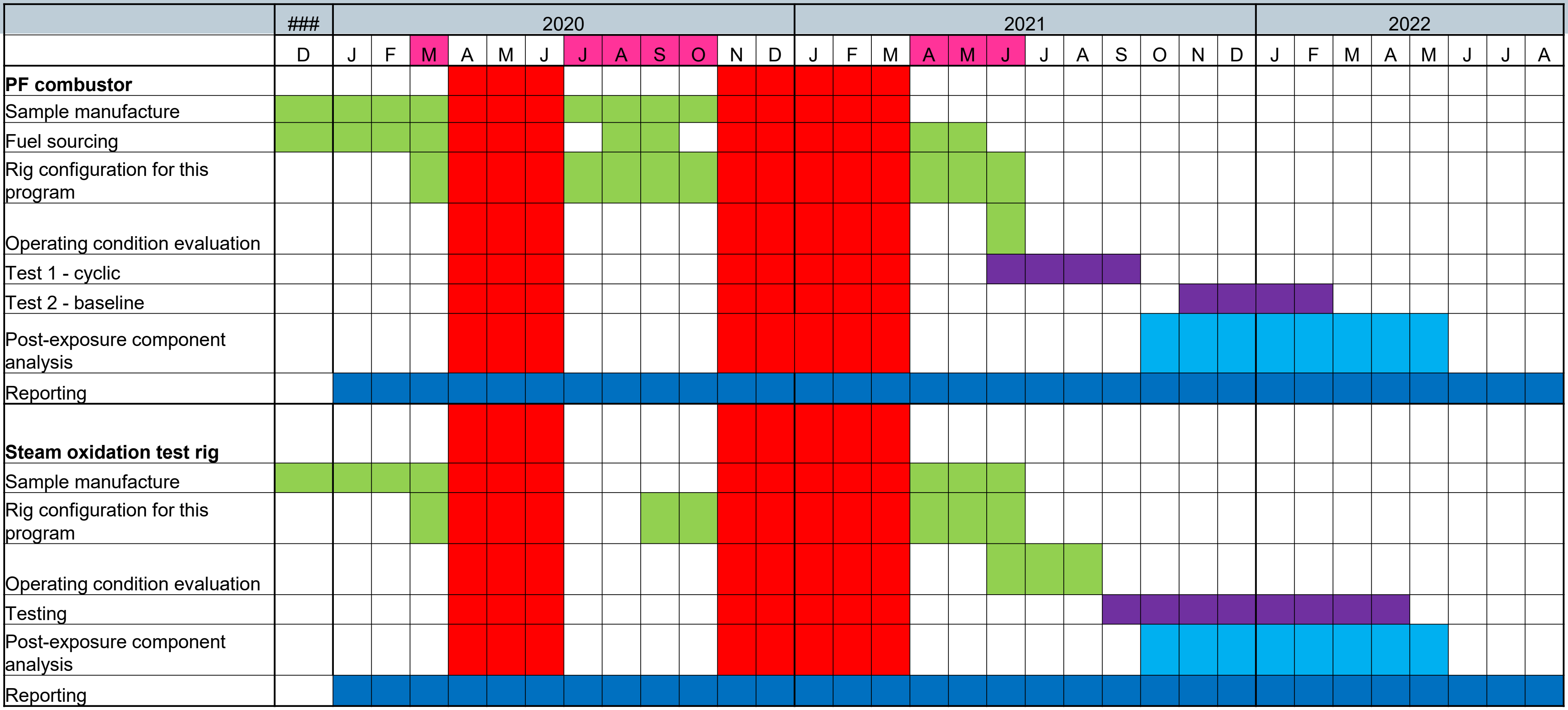

Superheater Tube Redesign – Laboratory Evaluation

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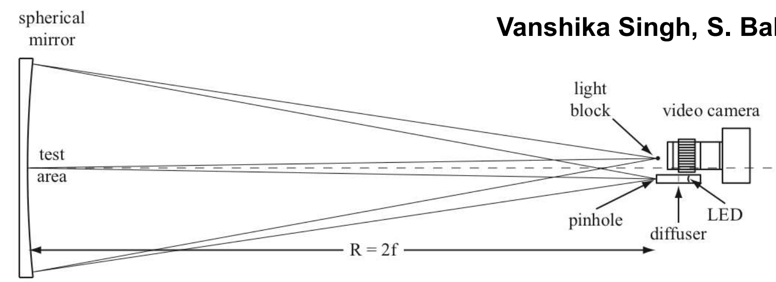
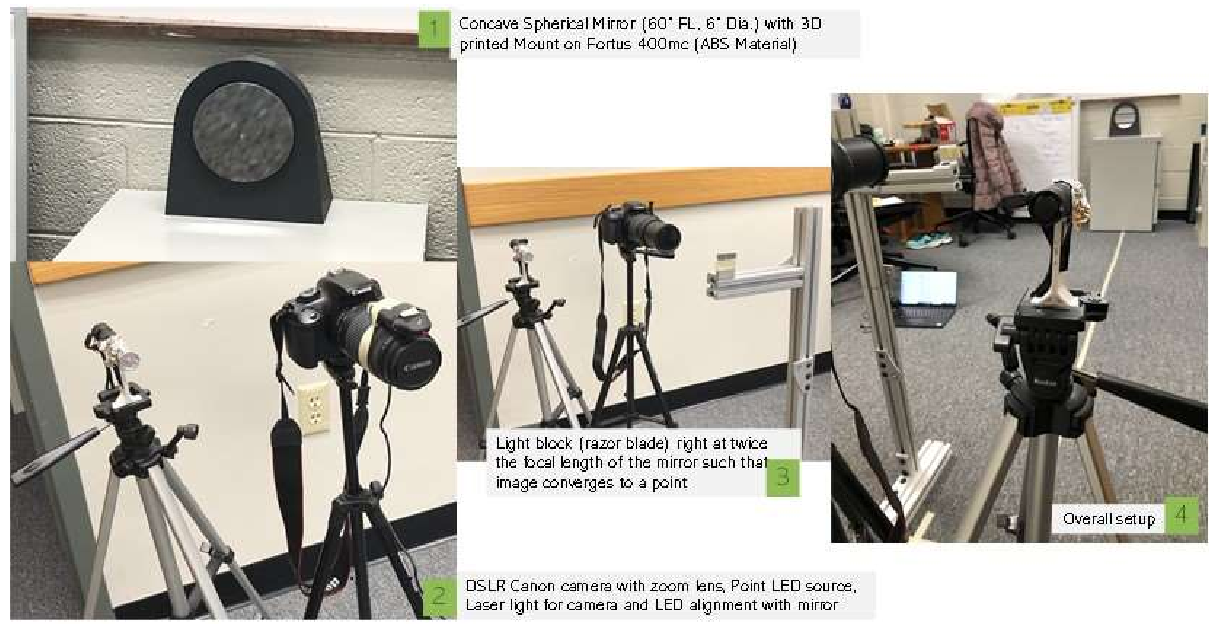
Schlieren Optics Setup: Experimental Setup to study flow behavior around the tube

Vanshika Singh, S. Babu, ORNL/UTK



https://sciencedemonstrations.fas.harvard.edu/presentations/schlieren-optics



Technique to visualize and study variation in flow of gases or change in air refractive index via a concave mirror, point source light, razor blade (light block), and a camera.

Principle of Schlieren Effect:

Change in the density of the fluid in front of the mirror causes change in the refractive index. For air and other gases, there is a simple linear relationship between the refractive index and the gas density, ρ, given by $n - 1 = k\rho$

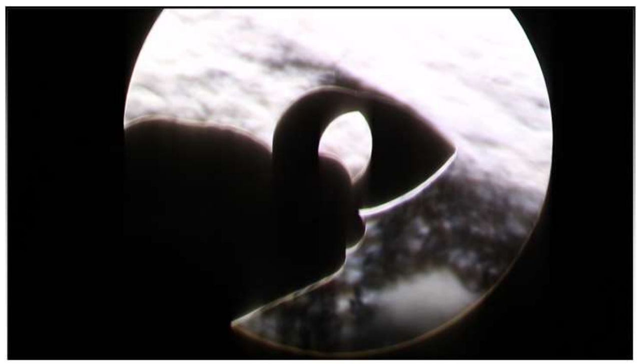
where k is known as the Gladstone-Dale coefficient

Schlieren Effect Videos

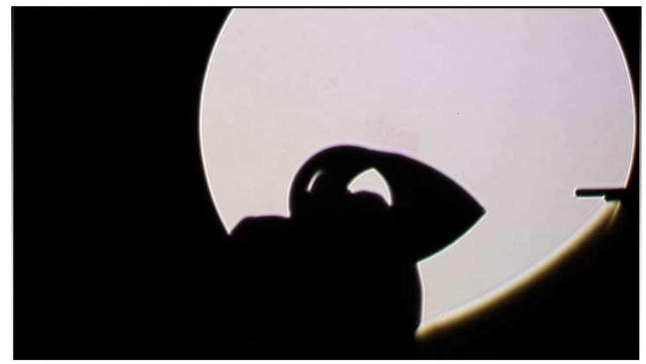
Vanshika Singh, S. Babu, ORNL/UTK

Circular tube under Fan Heater

Teardrop shape under Fan Heater



Teardrop shape under whiteboard cleaner spray



- This is just to show the feasibility of the schlieren optic setup
- Need to accurately capture to show the particle flow around the tube.

Next Steps:

1. Making the Schlieren Optic Experiment more deterministic by using controlled flow of particle hitting the tube surface.
2. Making fixtures to hold the tube and nozzle sprayer.
3. Performing parametric shape optimization on the tube surface to have optimum geometric dimensions using COMSOL optimization module.

Our Approach for Thermal Energy Storage for Fossil Plants

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Improve

- Plant ramp rate is not depending on the boiler constraints
- Plant turn down is not limited by the combustion instability limits
- Flexible part-load operation as boiler and turbine are separated
- Enhances plant reliability
- Respond quicker during frequency response
- Plant start-up time is reduced

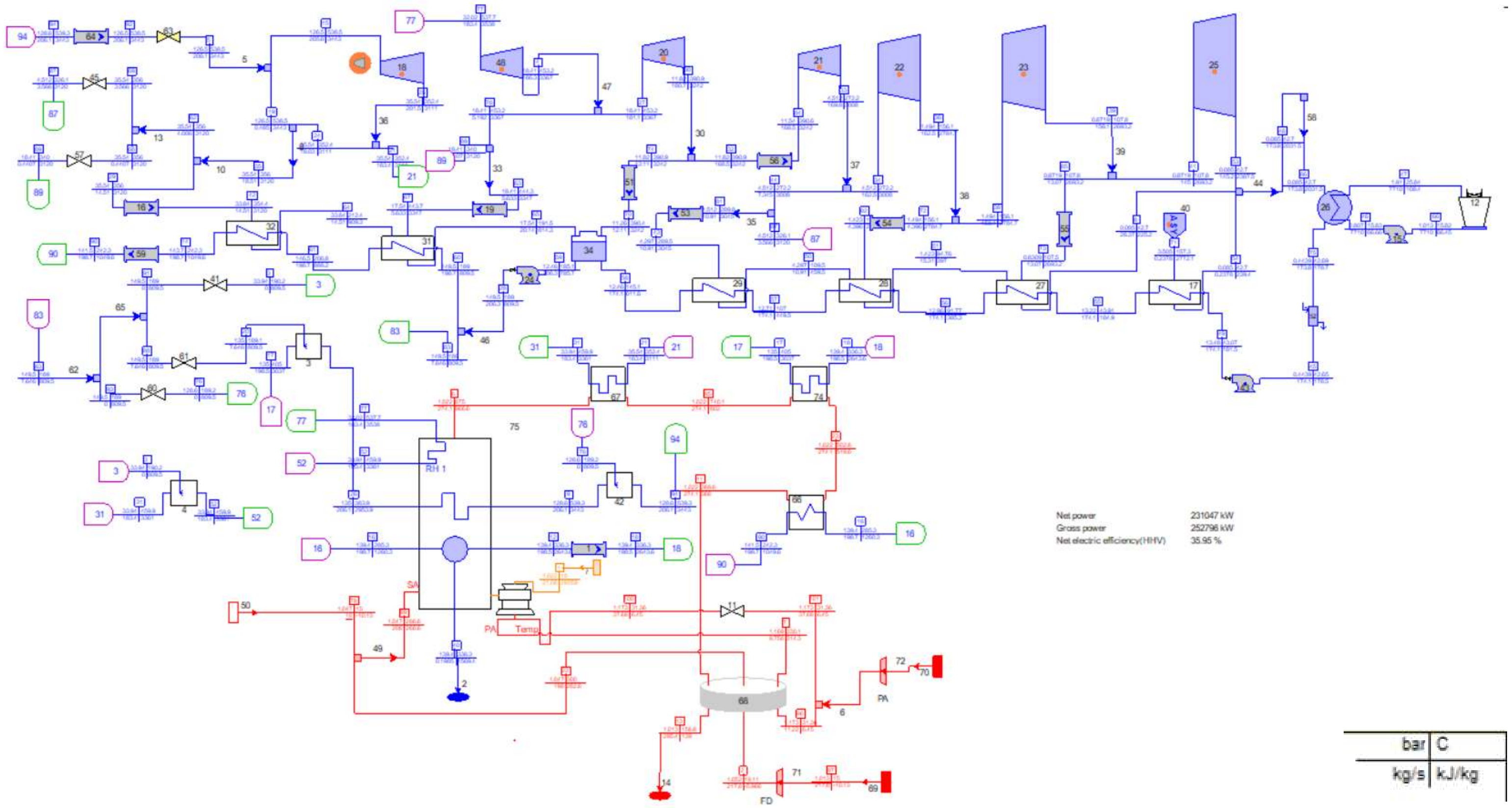
Research Questions

- What is the optimal plant configuration to integrate coal plant with TES in order to realise the benefits?
- What is the optimal temperature, size of storage to meet a particular objective?
- What type of TES is better suited for which purpose?
  - Direct steam accumulator
  - Direct feed-water storage
  - Indirect two-tank molten salt
  - Indirect molten salt-based Phase Change Material (PCM) selected based on the optimal integration temperature

Task 4.0 - Thermal Efficiency Optimization
Steady-State Thermodynamic Process Model

230MW$_e$ Sub-Critical Plant in USA

Turbo furnace coal fired two-pass boiler with natural circulation



What is the Capacity of two-tank TES?
230MW USA Plant

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Available thermal capacity for charging depends on,

- plant operating load as a minimum steam turbine flow/pressure needs to be maintained, therefore, the optimal storage size depends on the typical plant load profile
- Charging configuration : E.g. HRH steam branching reduces the pressure at IPT inlet, thus, HPT PR increases (CRH temperature reduces and increasing the boiler RH duty), and IPT PR reduces (LPT inlet temperature increases). The effect is minimised if the IPT control valve maintains a fixed pressure. Increasing the % mass flow reduces the ΔT

Charging: ~23MW$_{th}$, @50% load, ~47MW$_{th}$, @ 100% load

✓ Inlet : HRH line, 32 bar, 538^{o}C

✓ Return : IPT/LPT Cross-over Pipe, 11.8 bar, 390^{o}C

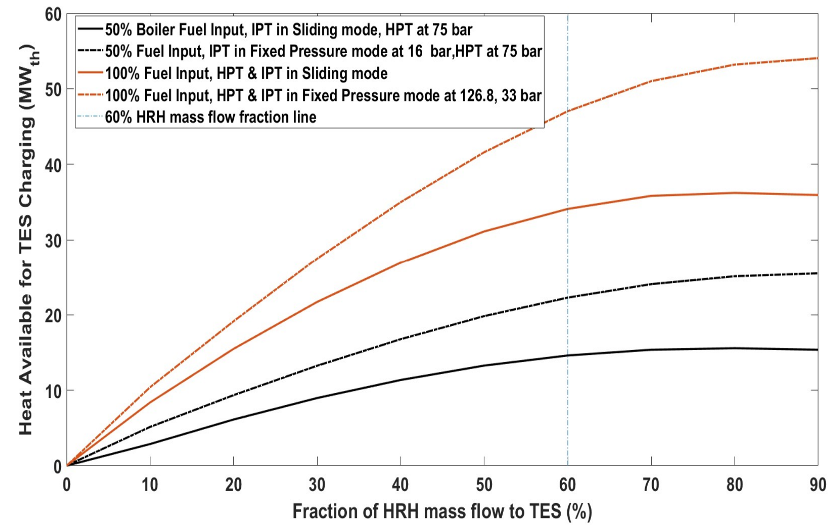
Discharging: ~32MW$_{th}$, @100% load, 12.5MW$_{th}$, @50% load

✓ Stored heat from TES is used to heat the top HP FWH's using additional heat exchangers

✓ Peak power is produced immediately due to more steam flow through the turbine, ~3.7% @ 100% load and ~1.6% @ 50% load

Optimal integration configuration that minimises the exergy destruction of both the process need to be investigated

Available Charging Capacity for TES



500 MW UK Plant (West Burton Plant)

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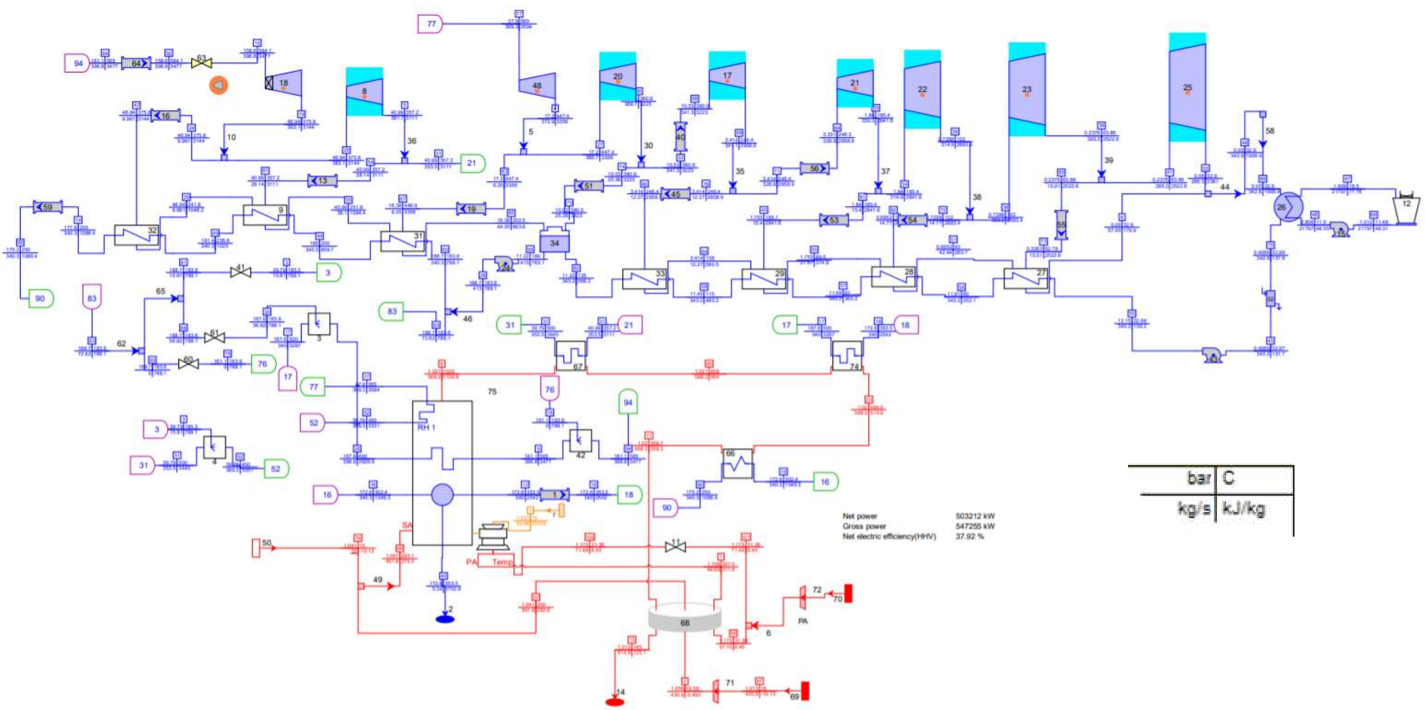

Plant Key Specification

Description	Unit	Value
Condenser Pressure	mbara	50
FW Heaters		3*LP+DA+3HP
FW exit Temperature	ºC	250
MS Pressure	bar	158.6
MS Temperature	ºC	565

Ultimate Analysis

Description	Unit	Value
Carbon	%wt	59.71
Hydrogen	%wt	3.8
Oxygen	%wt	5.49
Nitrogen	%wt	1.00
Sulphur	%wt	1.75
Chloride	%wt	0.55
Moisture	%wt	12.00
Ash	%wt	15.70
HHV	kJ/kg	24,643

Task 5: Scaleup and Technology Maturation Plan

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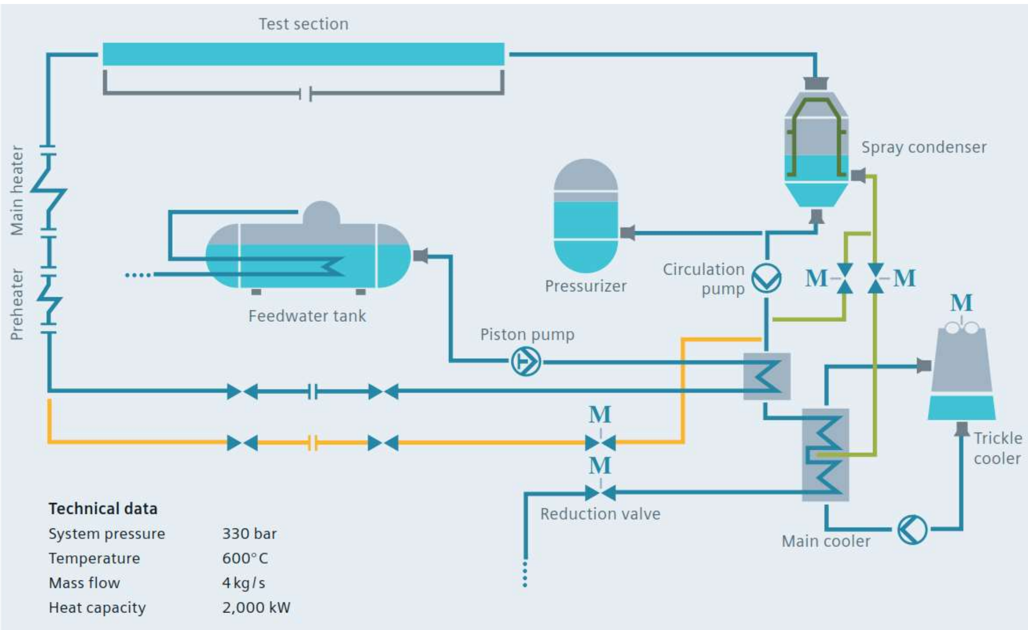
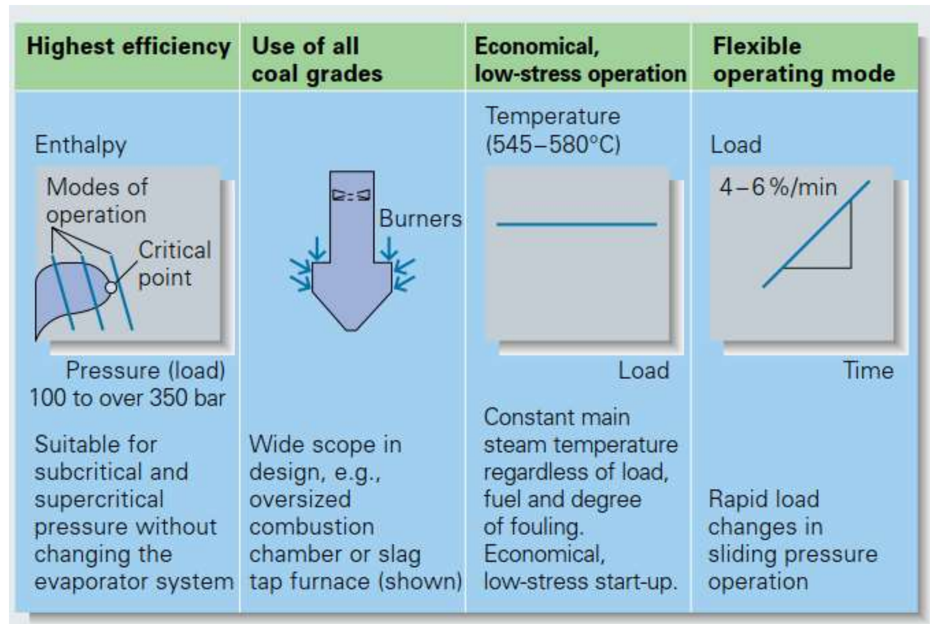
Siemens’ Benson test rig



Typical test parameters:

Pressure	25 ≤ p ≤ 280 bar	Heat flux	0 ≤ q ≤ 950 kW/m²
Mass flux	30 ≤ m ≤ 2,500 kg/(sm²)	Tube inner diameter	8 ≤ d ≤ 50 mm

Operational Flexibility



Conclusions

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- Design for additive manufacturing together with multiphysical topology optimization has been utilized to address critical failure mechanisms observed for tubes
- Redesigned tubes for optimized geometries printed using powder bed fusion and sent to Cranfield University for insertion into test matrix, together with existing materials
- Environmental testing of redesigned tubes with baseline tubes/welds will evaluate performance in specific operating environments targeted for cyclic operations of existing coal power plants.
- Rig testing for both combustion/steam oxidation testing delayed due to pandemic, to commence June 2021
- Thermodynamic modelling a TES system ongoing for charging/discharging opportunities to enable flexible operation of conventional plants.

- Transient model development in Dymola® is under underway and the detail model of the two types of TES will be integrated to realise the enhancement in plant flexibility
  - Sensible heat 2-tank system, HP system
  - PCM storage
- End deliverable is a comparison of TES approaches for US 230 MW and UK 500 MW coal power plants.