Modeling and Validation of Heat Transfer for Indirect SCO2 Coal-Fired Boilers

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Problem and Opportunity

- Require novel technology to meet future energy demands

- Indirect fired Supercritical Carbon Dioxide (sCO_2) is a promising technology
  - sCO_2 cycles can have higher thermodynamics efficiencies than traditional approaches
    - Capture more energy from the same source
    - Increased energy production + reduced emissions
  - sCO_2 power cycle is fuel and source agnostics
    - Biomass (e.g. sugarcane bagasse)
    - Municipal solid waste
    - Clean coal
    - etc.

- Careful design of the heat exchangers is required to obtain optimal efficiency

- Need accurate modeling or a lot of energy is lost through the stack

- Need a well validated sCO_2 design tool

Current Challenges

- Heat input over a narrow temperature range in sCO_2 cycle
  - Inefficient heat transfer results in high stack temperatures and energy/exergy loss
- Higher pressure for sCO_2 power cycles require careful cost optimization for higher TIT applications
- sCO_2 heat transfer – Potential buoyancy effects
  - Depending on operational conditions inside the boiler
  - Possible 4x difference between accepted heat transfer correlations
  - 2.5x variation in heat transfer coefficient circumferentially
- sCO_2 heat transfer – Size effects
  - Impact of buoyancy makes selection of tube size very critical
- sCO_2 heat transfer – Inclination/Orientation effects
  - Impact of buoyancy changes heat transfer performance depending on flow orientation
- Non-uniformity in heat flux
  - External radiation and convective conditions cause strong differences in heat flux
  - Significant impact on fatigue life for tubes and weldings

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Technical Objectives

- Develop a design tool for indirect fired sCO2 (at TRL 4 to 5)
- Fully validate the tool against realistic conditions
- Design tool will
  - provide techno-economic optimization
  - provide design optimized for minimal exergy loss and increased tube life
  - provide life estimate for the entire PC-boiler under prescribed operational transients
  - Can be extended to other heat exchange components of indirect fired sCO2 power cycle (air cooler, recuperative heat exchanger)
- Demonstrate the sCO2 design tool for a coal fired boiler
  - Coal is a critical source of energy in the United States and world
  - Accounts for ~30% of energy
  - Secure, abundant, and domestic energy source
  - Need better and more efficient ways to extract energy from coal that can also lend to carbon capture

Benefits

- Aid in the development of future high-efficiency power generation plants
- Provide the industry with a design tool for sCO_2
- Enhance the capabilities of IDAES
- Provide a design approach for an optimized pulverized coal boiler
- Support DOE Coal FIRST (Flexible, Innovative, Resilient, Small, Transformative)
- Better utilization of coal
- Reduction of emissions

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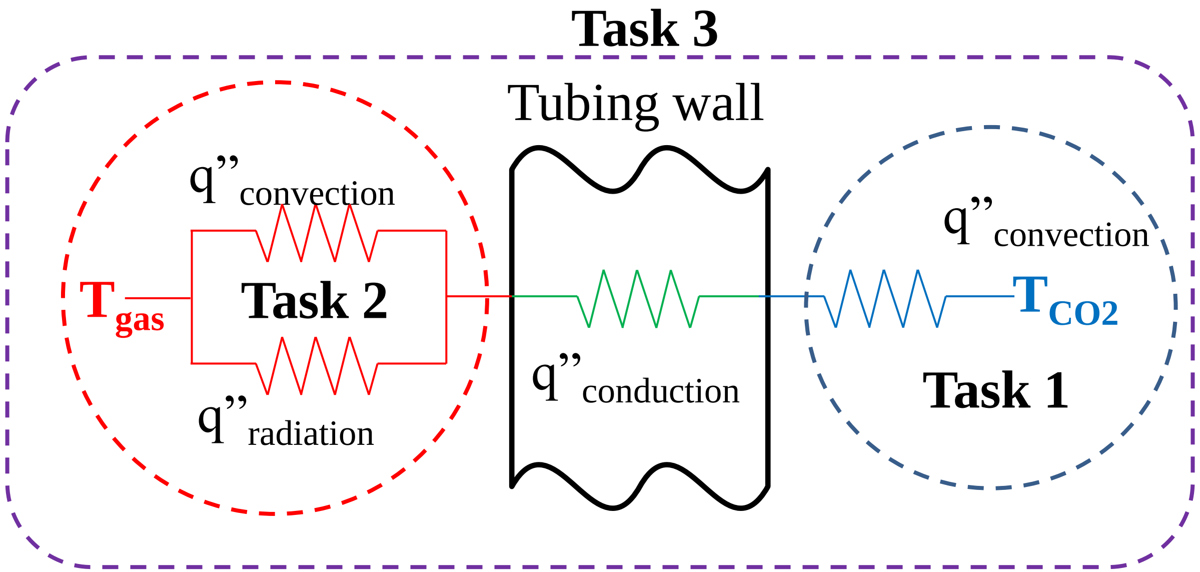
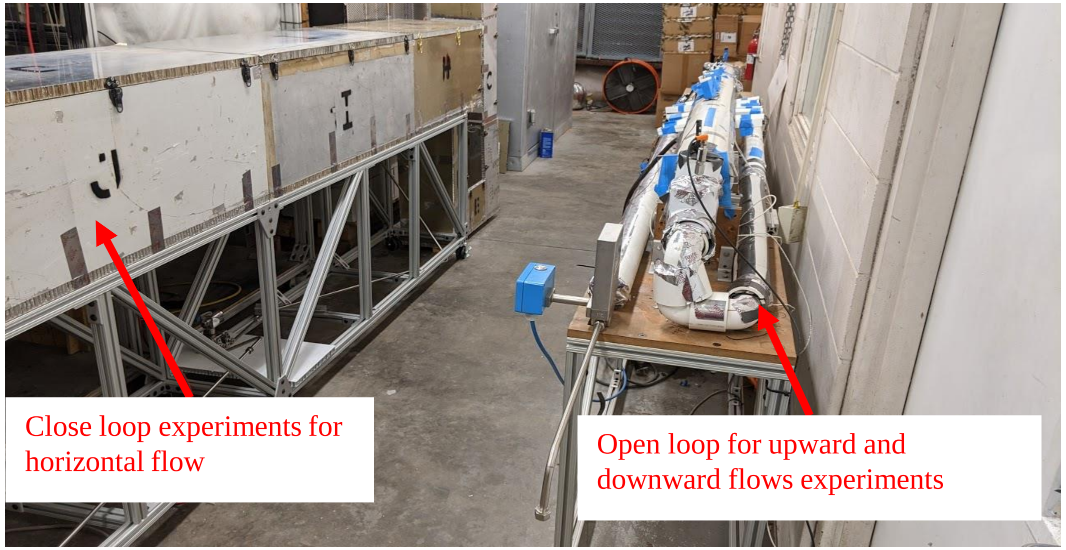
Tasks

- Task 1: Validation of heat transfer correlations for internal CO2 flow at boiler conditions
  - Milestone 1 – Experiments for internal sCO2 flow HTC at boiler conditions (Month 7)
  - Milestone 2 – HTC/Nu correlations development at the boiler conditions (Month 10)
- Task 2: Radiative-convective heat transfer model of heater external flow path
  - Milestone 1 –Extraction of convective and effective radiative heat transfer coefficients (Month 7)
- Task 3: Integrated Model & 1-D Optimization of PC-boiler for sCO2 cycle
  - Milestone 1 – Develop IDAES (or python/MATLAB) modules of heat transfer correlations for internal and external flow and pressure drop for internal flow (Month 8)
  - Milestone 2 – Multi-objective optimization framework setup for of PC-boiler design using the developed 1-D design code (Month 10)

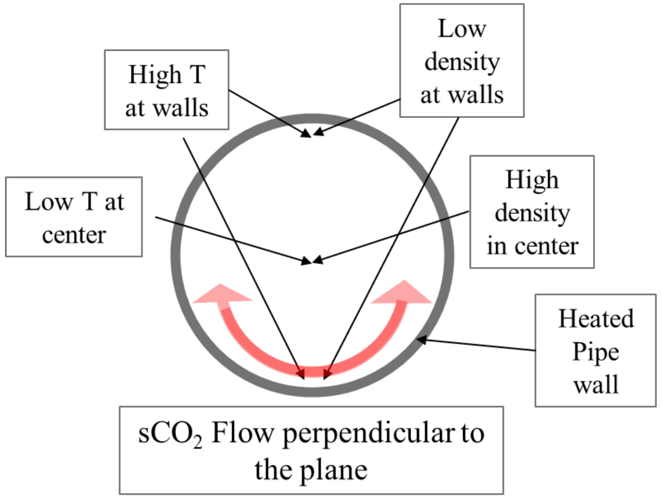


Task 1: Validation of heat transfer correlations for internal CO2 flow at boiler conditions

Experimental loop:



Internal flow heat transfer experiments with circular pipe geometry for horizontal, upward and downward flows:

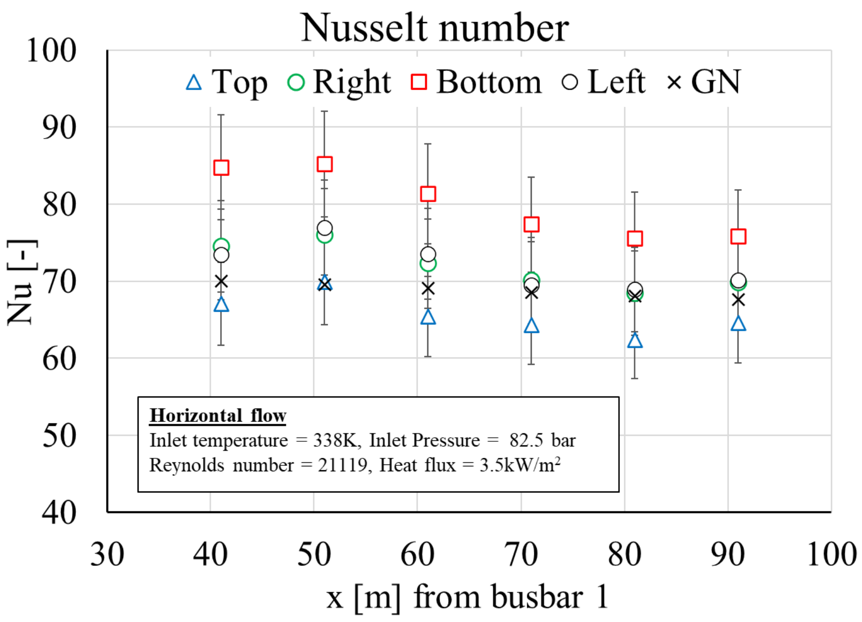


Natural convection effects perpendicular to primary flow

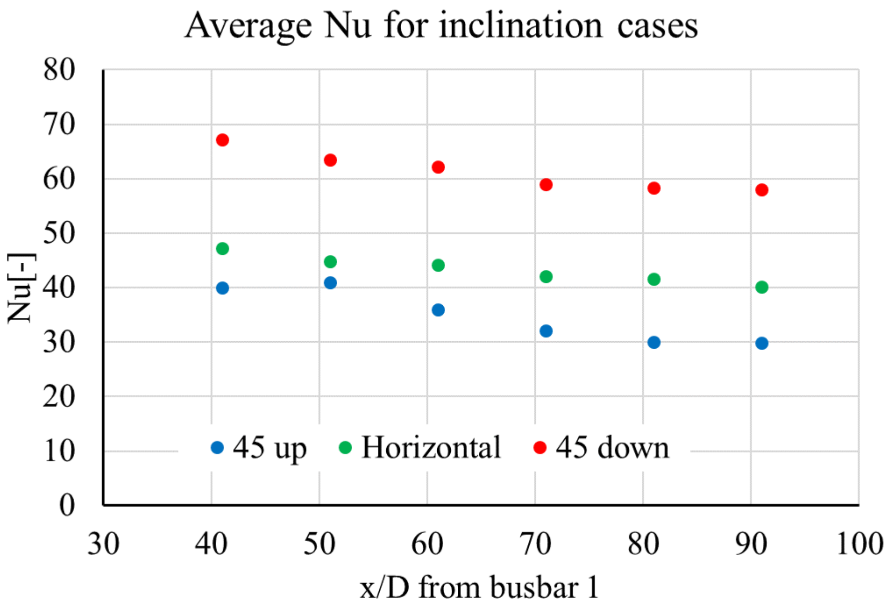
- Milestone 1 – Experiments for internal sCO2 flow HTC at boiler conditions (Month 7) 12/1/2020
  - Actual deliverable conditions: Tests with T<420K P<100bar without R-HEX (recuperative heat exchanger)
  - Actual deliverable date: January 2021
- Milestone 2 – HTC/Nu correlations development at the boiler conditions (Month 9) 3/1/2021
  - Actual deliverable conditions: Tests with T<800K P<100bar with R-HEX
  - Actual deliverable date: March 2021

Task 1: Validation of heat transfer correlations for internal CO_2 flow at boiler conditions

- Nusselt numbers are plotted at several axial locations and at 4 circumferential locations
- Even away from the critical point, there are effects of buoyancy on heat transfer
- Higher heat transfer at bottom surface and lower heat transfer at top surface
- Currently studying at which temperature away from critical point the effects of buoyancy start to diminish



- Nusselt numbers are plotted at several axial locations and at 4 circumferential locations
- For three cases with similar inlet conditions and with different angle and flow direction
- Downward flow shows highest heat transfer
- Buoyancy forces opposite to primary flow direction creating more turbulence hence increasing the heat transfer
- Upward flow has the lowest heat transfer



Upwards
Pin = 80.9 bar
Tin = 39.4^{o}C
Re = 16936

Horizontal
Pin = 78.6 bar
Tin = 39.2^{o}C
Re = 16593

Downwards
Pin = 80.2 bar
Tin = 39.8^{o}C
Re = 15890

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Task 2: Radiative-convective model of heater external flow path

- Radiative-convection model
  - Implemented into the IDAES model
  - Source: Ma, J., Eason, J.P., Dowling, A.W., Biegler, L.T. and Miller, D.C., 2016. Development of a first-principles hybrid boiler model for oxy-combustion power generation system. *International Journal of Greenhouse Gas Control*, *46*, pp.136-157.

- Convective Model
  - For large-scale utility boilers, Reynolds number is typically greater than 10^4 and the correlation for fully developed turbulent flow is used to calculate the Nusselt number

$$\mathrm{Nu}_{zone,j} = 0.026 Re_{zone,j}^{0.8} Pr_{zone,j}^{0.333} \left[\frac{\mu_{gas,j}(T_{zone,j})}{\mu_{gas,j}(\bar{T}_{wall})} \right]^{0.14}$$

  - If Reynolds number is less than 10^4, a constant Nusselt number for fully developed laminar flow at uniform surface temperature is used

$$\mathrm{Nu}_{zone,j} = 3.66$$

- Assumptions
  - Coal flow rate as a function of load
  - Coal HHV is fixed
  - Heat duty split from fire side to water wall
  - Platen superheater is fixed

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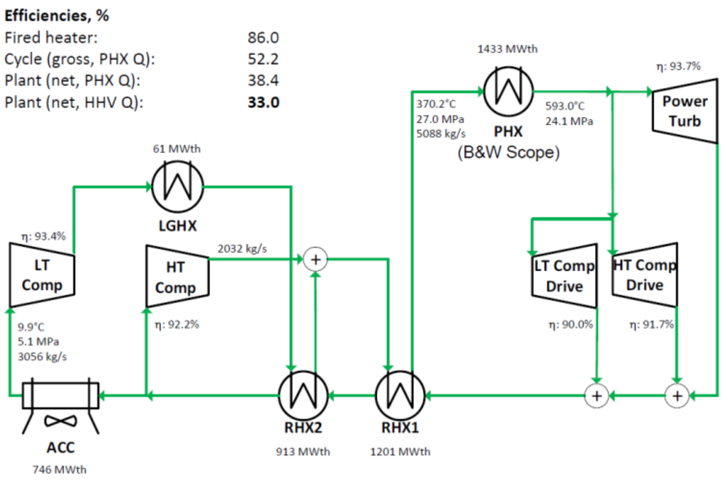
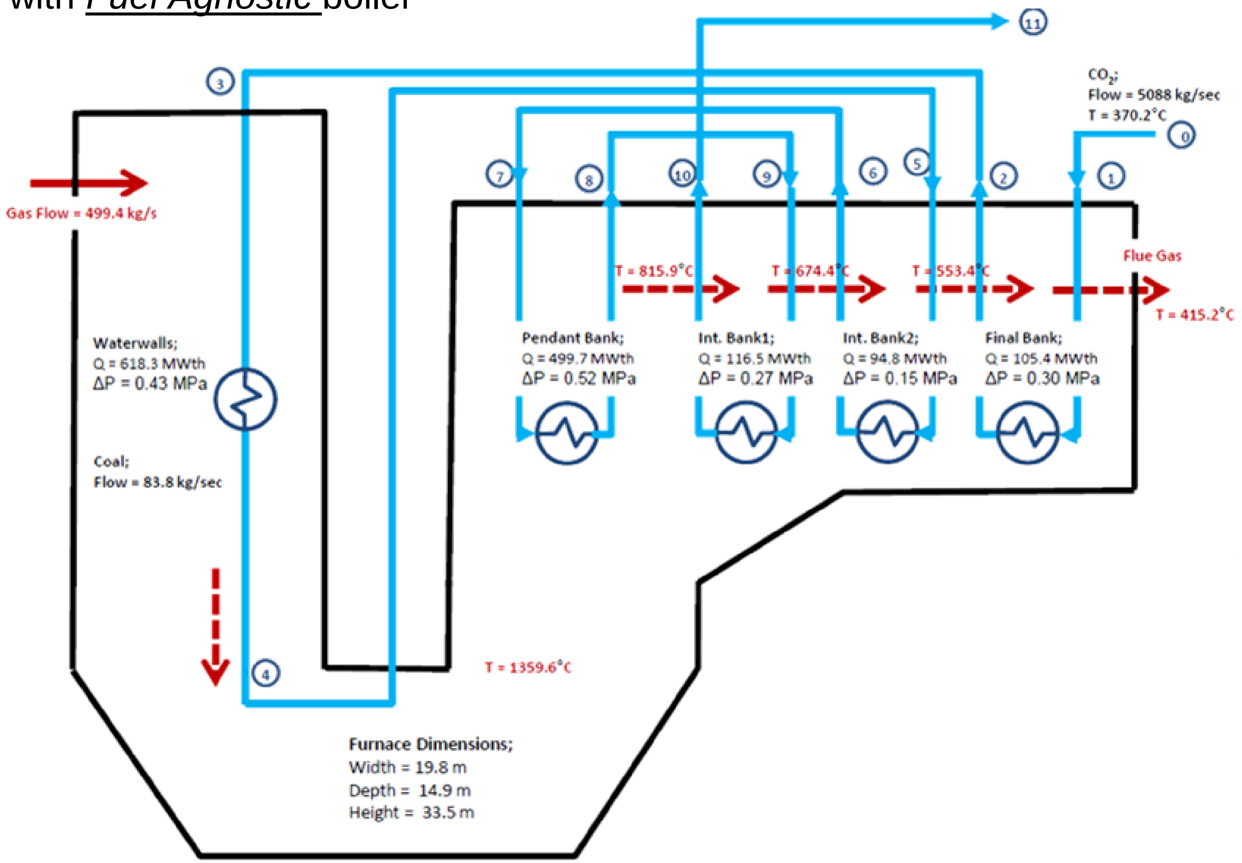
Task 3 Integrated Modeling & 1-D Optimization of PC-boiler for sCO_2 cycle (Use Case)

- Selected the EPRI pulverized coal fired boiler as a demonstration/use case that will be used for Tasks 3
  - Recompression sCO_2 cycle
  - Continued work will be focused on the simple sCO_2 cycle with *Fuel Agnostic* boiler



Point Location	T [Deg-C]	P [MPa]
0 – Heater Entrance	370.2	27.00
1 – Entrance to the Final Bank	370.2	26.95
2 – Final Bank Exit	386.3	26.52
3 – Waterwall Entrance	386.3	26.45
4 – Waterwall Exit	483.0	25.87
5 – Int. Bank 2 Entrance	483.0	25.9
6 – Int. Bank 2 Exit	497.8	25.51
7 – Pendant Bank Entrance	497.8	25.46
8 – Pendant Bank Exit	575.4	24.75
9 – Int Bank 1 Entrance	575.4	24.69
10 – Int Bank 1 Exit	593.0	24.26
11 – Heater Exit (to Turbine)	593.0	24.19



For a nominal 550 MWe design

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Task 3 Integrated Modeling & 1-D Optimization of PC-boiler for sCO2 cycle (Use Case)

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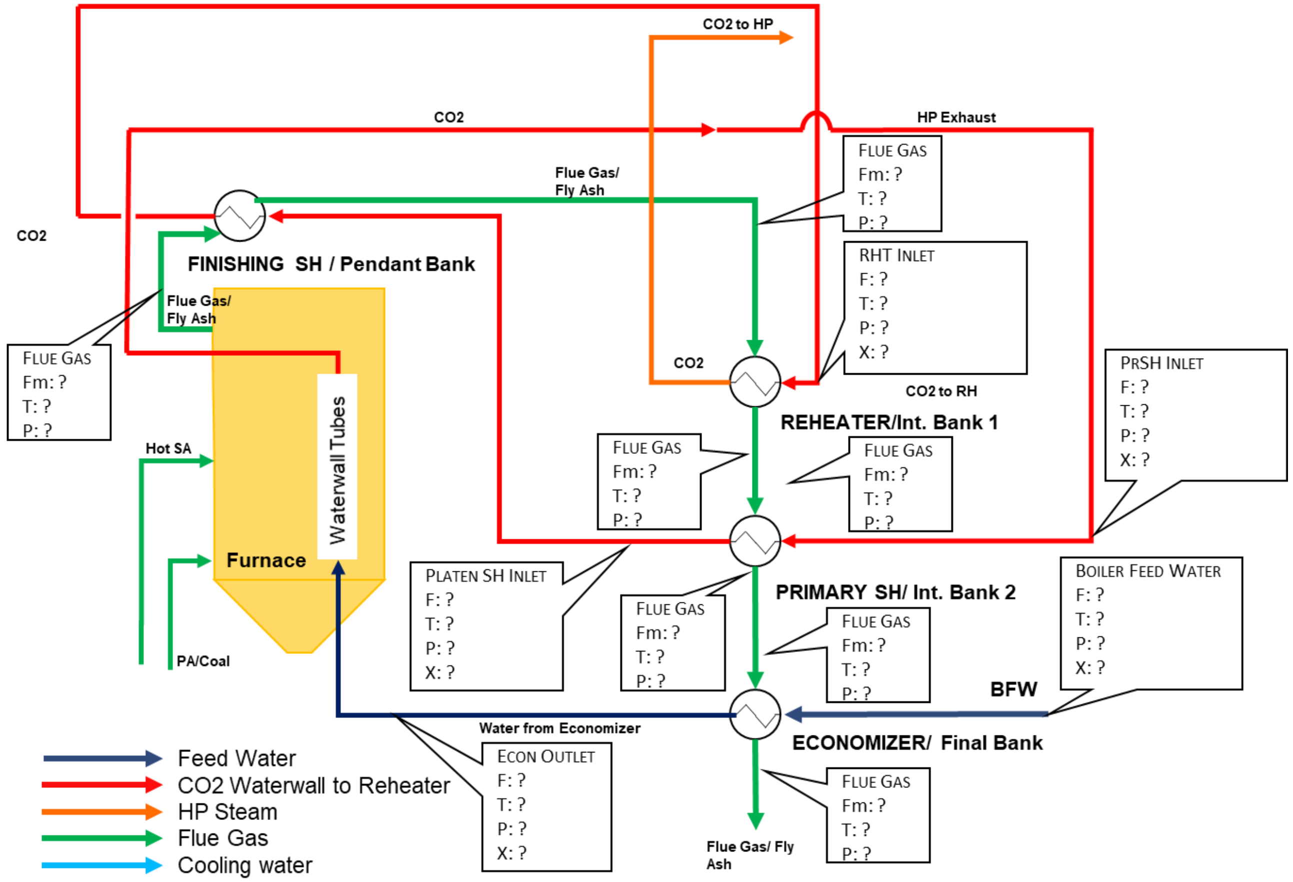
SUPERCRITICAL CO2 BOILER HX NETWORK FLOWSHEET



Legend	
F:	Flow (Mol/s)
FM:	Flow mass (kg/s)
T:	Temperature (K)
P:	Pressure (Pa)
x:	Vapor Fraction

Task 3 Integrated Modeling & 1-D Optimization of PC-boiler for sCO2 cycle (Waterwall - Setup)

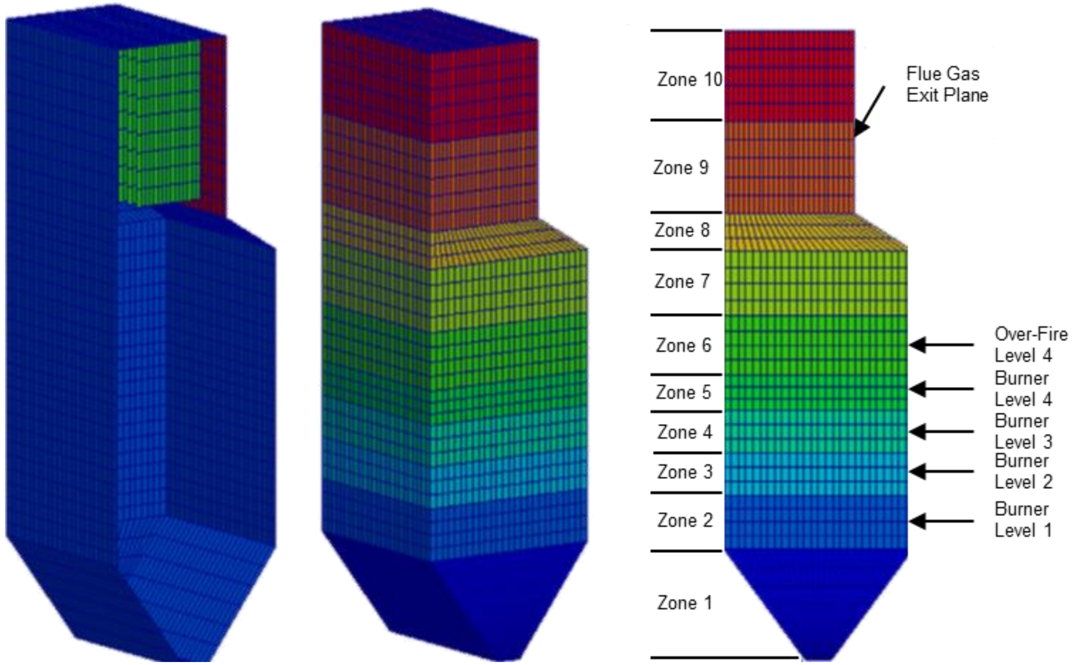
Number of burner levels	4	-
Number of overfire levels	1	
Number of superheater panels	11	
Number of vertices of superheater polygon	4	
Furnace depth (X)	15.5448	m
Furnace height (Y)	51.816	
Furnace width (Z)	15.8496	
X of hopper bottom of front wall	6.7056	
X of hopper bottom of rear wall	8.8392	
X of nose tip	10.668	
Y of hopper knuckle	9.144	
Y of the bottom of nose slope	33.6804	
Y of the nose tip	36.8237	
X of superheater vertex 1	3.048	
X of superheater vertex 2	9.144	
X of superheater vertex 3	9.144	
X of superheater vertex 4	3.048	
Y of superheater vertex 1	38.7096	
Y of superheater vertex 2	38.7096	
Y of superheater vertex 3	51.816	
Y of superheater vertex 4	51.816	
Y of burner level 1	12.192	
Y of burner level 2	14.9352	
Y of burner level 3	19.2024	
Y of burner level 4	21.9456	
Y of overfire port level 1	25.1206	

Fuel data

Mass % of C	64.49
Mass % of H	4.44
Mass % of O	9.25
Mass % of N	1.18
Mass % of S	0.64
Mass % of moisture	8.86
Mass % of ash	11.14
Mass % of volatiles	40
High heating value (kJ/kg)	26,360

Input parameters

	Air-fired case	Oxy-fired case	
Total coal flow rate	50.28		kg/s
Total air/O2 flow rate	512.2104	102.44	
Primary stream temperature	338.71	355.37	K
Secondary stream temperature	548.71	533.15	
Coal flow rate per burner level	12.5714		kg/s
Primary stream flow per burner level	24.7658	22.6285	
Secondary stream flow per burner level	72.8268	83.1027	
Overfire stream flow rate	121.84	83.7886	
Furnace pressure	86,126		Pa



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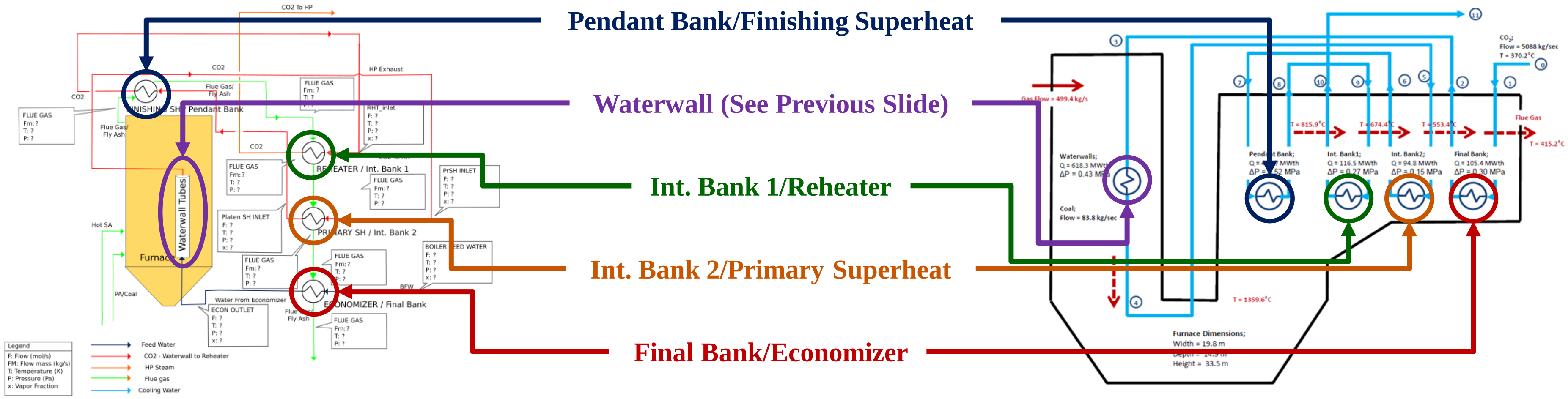
Input Parameters for the heat exchangers

	Final Bank	Int. Bank 2	Int. Bank 1	Pendant Bank	Units
Inner diameter	0.041/ 1.624	0.041/ 1.624	0.041/ 1.624	0.041/ 1.624	m/in
Outer diameter	0.0508/ 2	0.0508/ 2	0.0508/ 2	0.0508/ 2	
Thickness	0.0047 / 0.188	0.0047 / 0.188	0.0047 / 0.188	0.0047 / 0.188	
Pitch of tubes between two neighboring columns (in y direction)	0.127/5	0.127/5	0.127/5	0.127/5	
Pitch of tubes between two neighboring rows (in x direction)	0.076/ 3	0.076/ 3	0.076/ 3	0.076/ 3	
Tube length	16.27/ 640.92	16.27/ 640.92	16.27/ 640.92	16.27/ 640.92	m / ft
Number of tube rows in the direction of shell side	22	20	12	16	-
Number of tube columns in the cross section plane	80	80	150	250	
Number of inlet tube rows	8	8	6	6	
Elevation difference (outlet - inlet) for static pressure calculation	50	50	50	50	m



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Task 3 Integrated Modeling & 1-D Optimization of PC-boiler for sCO2 cycle (Results)

- Techno-economic calculation framework setup for IDAES

Weiland, N.T., Lance, B.W. and Pidaparti, S.R., 2019, June. SCO2 power cycle component cost correlations from DOE data spanning multiple scales and applications. In ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition. American Society of Mechanical Engineers Digital Collection.

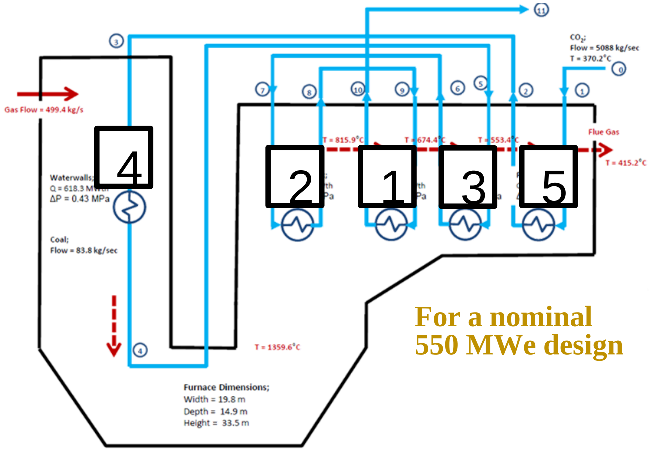
$$f_{T,PHX} = \begin{cases} 1 & if\ T_{max} < 550\ °C \\ 1 + 5.4 \times 10^{-5}(T_{max} - 550\ °C)^2 & if\ T_{max} \geq 550\ °C \end{cases}$$

$$C_{CF,PHX} = 820{,}800\ Q^{0.7327} \times f_{T,PHX}$$

$$C_{CF,PHX} = 1{,}248\ UA^{0.8071} \times f_{T,PHX}$$

Q [MWth] - the thermal heat duty

$f_{t,phxthe}$ - temperature correction factor



For a nominal 550 MWe design

	Power		PC Boiler Cost
	[MW]		[M$]
	EPRI –CASE 1	IDAES	IDAES
Reheater	116.5	116.76	29.28
Finishing Superheater	499.7	480.19	77.94
Primary Superheater	94.8	98.5	23.7
Waterwall	618.3	618	91.03
Economizer	105.4	108.51	25.44
Total	**1433**	**1421.96**	**247.39**

= $173 / kW

		sCO2										Flue gas		
		IDAES	EPRI	IDAES	EPRI		IDAES	EPRI	IDAES	EPRI				
		P in		P out		m	T in		T out		T in	T out	m
		[MPa]				[kg/s]	[K]						[kg/s]
1	**Reheater**	25.28	24.69	24.86	24.26	5088	846.78	848.55	864.82	866.15	1164.91	1046.34	499.4
2	**Finishing Superheater**	25.52	25.46	25.28	24.75		771.64	770.95	846.78	848.55	1632.75	1164.91	
3	**Primary Superheater**	26.27	25.79	25.52	25.51		756.63	756.12	771.64	770.95	1046.34	944.26	
4	**Waterwall**	26.27	26.45	26.27	25.87		659.63	659.45	756.63	756.15		1632.75	
5	**Economizer**	26.95	26.95	26.27	26.52		643.35	643.35	659.63	659.45	944.26	829.18	

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Commercialization – Product

- Product: Design/optimization tool for sCO_2 power plants with initial focus on PC Boilers
  - Using IDAES as a starting framework
  - Incorporate necessary physics into the framework
    - Correlations/equations for sCO_2 heat transfer coefficients
    - Radiative and convective heat flux
  - Validation data for heat transfer coefficients
    - Industry states that this is a critical roadblock
    - Needed to improve models
    - Needed to gain confidence in designs
    - Better data would allow companies to reduce their design margins and reduce cost
  - Transition to other components

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Commercialization – Market Outlook

- Coal is the leading fuel for electricity world wide
  - Global coal consumption will increase in the foreseeable future
- Several pilot plants that use sCO2 are being constructed in the US
  - Use Natural Gas, Solar, Pulverized Coal
- Countries like China, India, and South Korea have plans to construct new coal-fired plants based on sCO2 technology

Country	Current and Planned Capacity (Mwe)		
	Subcritical	Supercritical	Ultrasupercrtical
Bangladesh	561	680	3,320
Indonesia	26,780	3,580	2,315
Malaysia	8,529	0	4,160
Philippines	9.901	1,336	0
Thailand	5,181	1,300	0
Vietnam	16,545	5,532	1,800

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Potential Future Work

- Design/Optimization/Control software for an indirect-fired sCO2 power cycle using IDAES platform
  - Overall framework architecture with multi-objective optimization; energy, exergy and techno-economic analyses; and transient analysis for various indirect-fired and waste heat recovery conditions
  - Consideration of material fatigue for heat exchange tubes and welds
  - Comparison of various control strategies
  - Comparison of cost and techno-economical for sCO2 and steam-Rankine Cycle
- Radiative-convective heat transfer model of heater external flow path for multiple sources of energy using IDAES platform
  - Incorporation of spatial distribution of radiative loading, through detailed simulation
  - Consideration of multiple sources of thermal energy, including MSW
- Extending the code for heat rejection (to air or water) and recuperative heat exchangers using IDAES platform
  - Transient analysis with variation of ambient conditions
  - Tracking of pinch point, and determining impact on the cycle and the other components
  - Inclusion of impact on lifecycles cost and condition-based-monitoring
- Incorporation of sCO2 heat transfer and flow/leakage correlations based on experimental data
  - Using the experimental facilities available at UCF
- Validation through testing of the heat exchangers under application-representative conditions

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