A Performance and Economic Comparison of Partial Cooling and Recompression sCO_2 Cycles for Coal-fueled Power Generation

The 7th International Supercritical CO_2 Power Cycles Symposium,
February 21 - 24, 2022, San Antonio, Texas

Sandeep Pidaparti, PhD
NETL Support Contractor

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Authors and Contact Information

Sandeep R. Pidaparti[1,2], Charles W. White[1,2], Nathan T. Weiland[1]

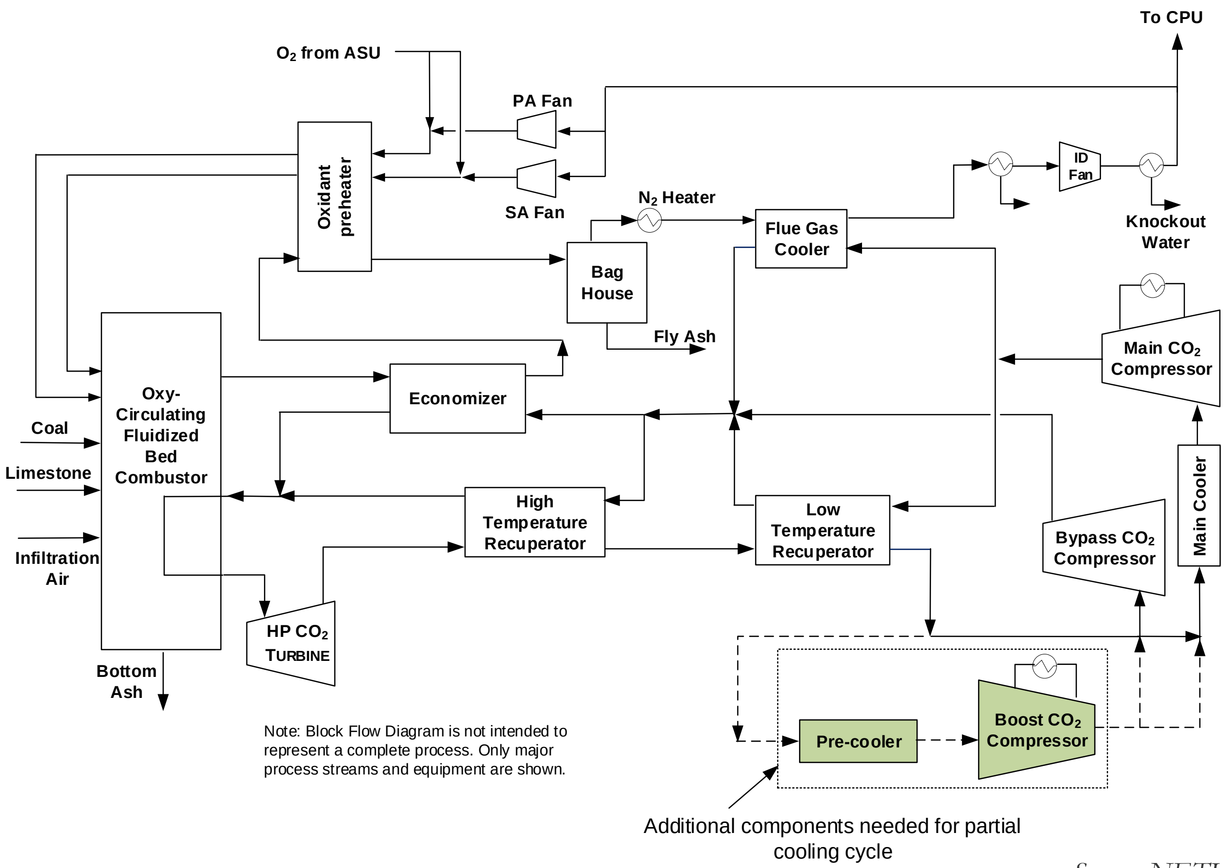
[1] National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA

[2] NETL Support Contractor, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA

Overview of Indirect sCO_2 Power Cycles

Background

- **Indirect sCO_2 power cycles are expected to offer higher plant efficiencies than steam Rankine cycles**
  - Smaller turbomachinery possible due to low pressure ratio relative to steam Rankine cycles
  - sCO_2 power cycles have higher flow rates and are much more sensitive to pressure drops than steam cycles
- **Recompression cycle (RC) is the most widely investigated configuration**
  - Operates over a relatively narrow temperature window of heat addition
- **Partial cooling cycle (PCC) can be beneficial in certain applications**
  - Pressure ratios higher than RC
  - Pre-cooler and boost compressor are needed to accommodate higher pressure ratios



Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

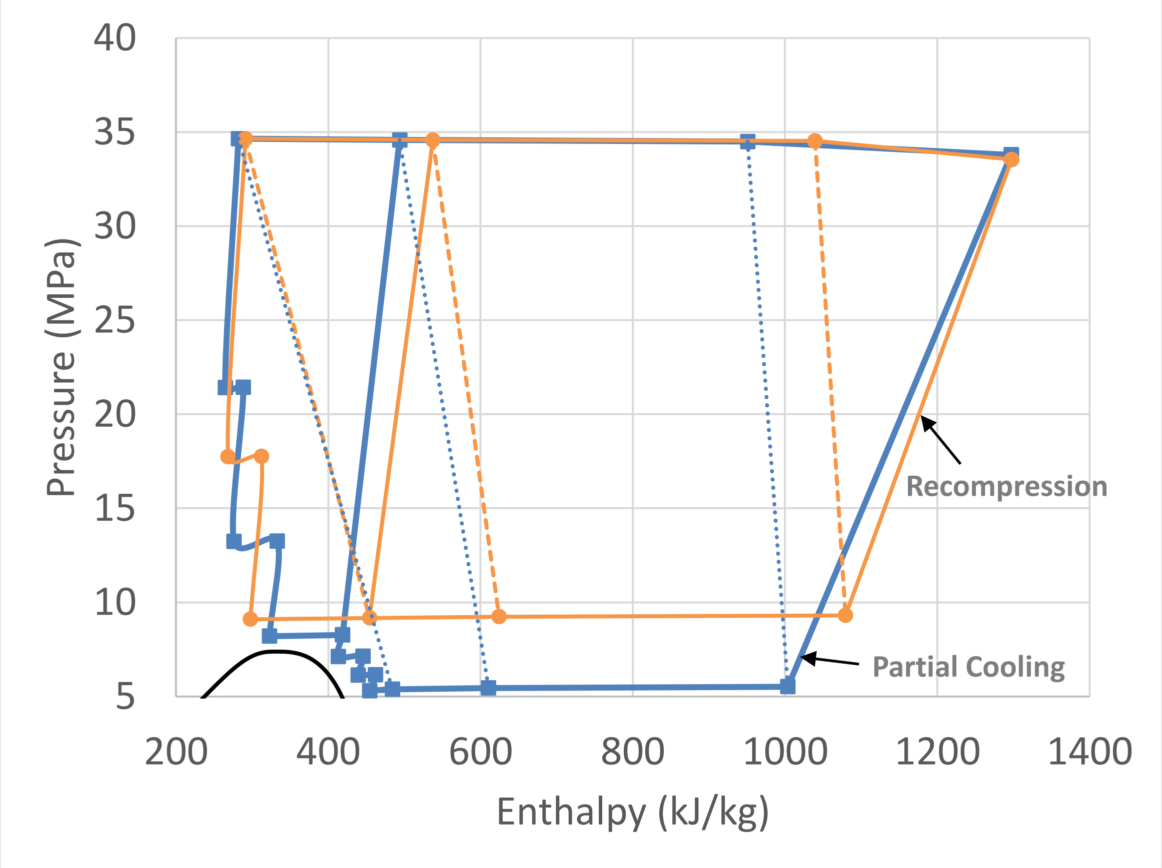
Additional components needed for partial cooling cycle

Source: NETL

Overview of Indirect sCO_2 Power Cycles

Background, Cont'd

- **Advantages of partial cooling cycle over recompression cycle**
  - Increases specific power and reduces sCO_2 flow rate resulting in lower pressure drops
  - Broadens the temperature range of heat addition potentially reducing heater costs
  - Lower recuperation duties, size and costs
- **Disadvantages of partial cooling cycle over recompression cycle**
  - May lower cycle and plant efficiencies
  - Additional equipment needed will increase the complexity and contributes to the capital cost
  - Larger pressure ratio will likely increase the size of turbomachinery equipment



Source: NETL

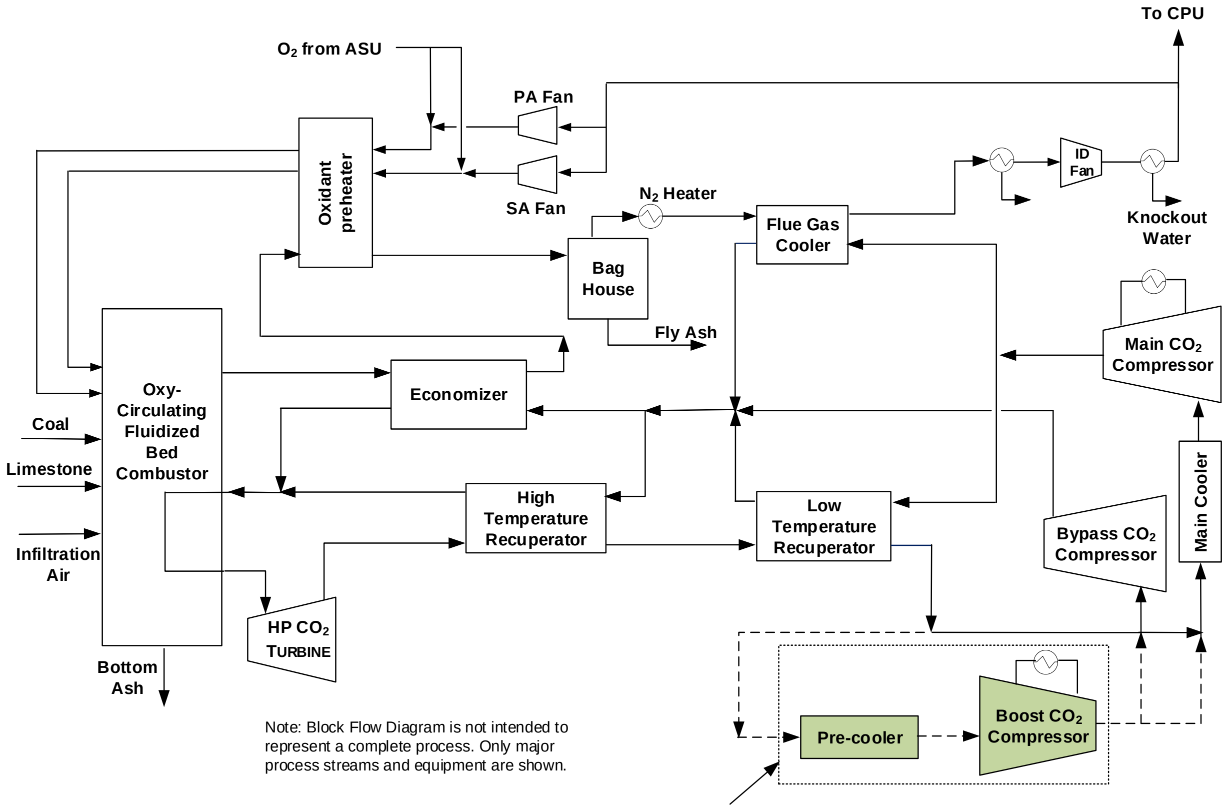
Study Objectives

- **Conduct techno-economic analysis for recompression Brayton cycle and partial cooling cycle**
  - Compare performance and cost of electricity (COE) of both the cycles for coal-fired power plants
  - Explore ways to lower COE by considering primary heater pressure drop vs cost tradeoff
  - Examine effect of turbine reheat on plant efficiency and COE
- **Expected contributions of this study to research community:**
  - Shed light on application of partial cooling cycle for coal-fired power plants
  - Highlight the importance of primary heater design

Modeling Approach

Design and Assumptions

- **Heat source is an oxy-fired circulating fluidized bed (CFB) combustor**
  - Illinois No. 6 coal fed to the atmospheric pressure CFB along with limestone that is added for sulfur capture
  - Oxygen provided by a low-pressure air separation unit (ASU)
  - Bed temperature is assumed to be 871.1°C (1600°F) with ~99% carbon conversion and 1% heat loss
- **Combustion heat is transferred to the power cycle via tube banks within the combustor**
  - Economizer and flue gas cooler maximize heat recovery – These operate in parallel to the recuperators and are typically not needed for nuclear, CSP applications



Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

Additional components needed for partial cooling cycle

Source: NETL

Modeling Approach

Design and Assumptions, Cont'd

- **Steady-state model of both the plants was developed using Aspen Plus software**
  - Net plant power output ~ 550 MWe
  - CO_2 thermophysical properties calculated using Span-Wagner equation of state via REFPROP
- **Recuperators and coolers are modeled as counterflow PCHEs**
  - 1-D discretized heat exchanger model is used to calculate *UA* and detect internal pinch points

Parameter	Recompression cycle	Partial cooling cycle
Turbine inlet temperature (°C)	760	
Coolers outlet temperature (°C)	35	
Cycle minimum pressure (MPa)	9.1	5.3
Cycle maximum pressure (MPa)	34.6	
Cycle intermediate pressure (MPa)	-	8.27
Number of compressor intercoolers (Main/Boost compressor)	1	2
Minimum recuperator temperature approach (°C)	5.6	
Recuperator, cooler pressure drops (kPa)	68.9	
Intercooler pressure drops (kPa)	13.8	
Turbine isentropic efficiency (%)	92.7	
Compressors isentropic efficiency (%)	85	

Modeling Approach

Design and Assumptions, Cont'd

- **A forced draft wet cooling tower is used for heat rejection from plant**
  - Ambient dry and wet bulb temperatures are 15°C and 10.8°C respectively (Midwestern U.S.)
- **For Cases with turbine reheat**
  - Single stage of reheat is used and pressure ratio of main and reheat turbines is assumed to be equal
- **Following additional constraints were imposed for plant modeling:**
  - Split flow between compressors adjusted such that
    - High pressure CO_2 temperature exiting LTR = Bypass compressor outlet temperature
  - Split flow between LTR and flue gas cooler adjusted such that
    - Flue gas cooler CO_2 outlet temperature = High pressure CO_2 temperature exiting LTR
  - Split flow between HTR and economizer is adjusted such that
    - Economizer CO_2 outlet temperature = High pressure CO_2 temperature exiting HTR

Modeling Approach

Economic Analysis

- **Based on steady-state modeling results, operating conditions of the cycle and balance of plants are used to estimate equipment capital costs**
  - Standard NETL cost estimating methodology is used to calculate the total plant cost (TPC) which includes the capital costs, installation, contractor fees and contingencies
  - COE includes contributions from capital costs, fixed operation and maintenance (O&M) costs, variable O&M costs, fuel costs as well as transportation and storage (T&S) costs for captured CO_2
- **No oxy-CFB cost estimates are available in public domain for sCO_2 power cycles**
  - A simplified CFB design tool was developed to calculate the capital cost of CFB with reasonable accuracy
- **Rest of the sCO_2 power cycle components capital costs are calculated using algorithms developed under prior work for indirect sCO_2 power cycle applications**
  - Further details of the economic analysis methodology can be found in the paper

Simplified CFB design tool

- **A simplified CFB model was developed as part of this study**
  - Allows to capture the impact of sCO_2 pressure drop, turbine inlet temperature, pressure and choice of reheat/non-reheat on CFB cost, at least in a qualitative sense
  - Model includes a bottoms-up CFB cost estimate derived using STEAMPRO and PEACE software package
- **Bottoms-up CFB cost breakdown is consistent with the STEAMPRO breakdown**
  - Sub-accounts, SA1 and SA2 includes the material and fabrication costs of radiative and convective tube banks
  - Sub-account, SA3 include the interconnecting piping, cyclones, refractory etc.
  - Sub-account, SA4 include the oxidant pre-heater (cost calculated using UA scaling derived from STEAMPRO)
  - Sub-account, SA5 include rest of the CFB (cost calculated using heat duty scaling derived from STEAMPRO)

CFB cost sub-accounts	Description
SA1	Furnace radiative tube banks
SA2	Convective tube banks
SA3	Interconnecting piping, cyclones, refractory etc.
SA4	Tubular oxidant pre-heater
SA5	Rest of the CFB (Soot blowers, ducts, feeders, fans, structural)

SA1 and SA2 are function of tube sizes, tube material, working fluid temperature, pressure and driving forces

Simplified CFB design tool, Cont'd

- **Sub-accounts SA1, SA2 costs are calculated using a tube bank sizing and cost model**
  - Allows user to select several alloys for tube, tube diameters
  - Calculates required tube wall thickness, heat transfer area, working fluid pressure drops (either steam/sCO_2) for specified process conditions
  - Flue gas heat transfer coefficients are taken from STEAMPRO and are assumed to be same for sCO_2 cycles
  - Steam/sCO_2 side heat transfer coefficients are calculated using Dittus-Boelter correlation
  - Steam/sCO_2 side pressure drop calculated using Colebrook friction factor correlation
  - Refer to the paper for further details

Model Inputs	Model Outputs
Steam/sCO_2 flow rate	Tube bank heat duty
Steam/sCO_2 inlet pressure and temperature	
Steam/sCO_2 outlet temperature	
Flue gas inlet temperature	Driving force ($LMTD$)
Flue gas outlet temperature	Steam/sCO_2 pressure drop
Tube material	Required heat transfer area
Tube outer diameter	Tube wall thickness and maximum wall temperature
Tube length	Tube bank cost

Simplified CFB design tool, Cont'd

- **CFB design tool was calibrated with STEAMPRO data for two cases**
  - Both cases have a net power output of ~550 MWe, turbine inlet temperature and pressure of 760 °C and 29.6 MPa respectively with single stage of reheat
  - Only difference between these cases is arrangement of tube banks resulting in different driving forces
- **Interconnecting piping costs are scaled with heat duty (No data available)**
  - Difference between calculated and STEAMPRO costs to <±4%
  - Interconnecting piping costs are also a function of working fluid pressure, temperature and tubing diameter etc.

CFB cost sub-accounts	Description	Case1	Case2
SA1	Furnace radiative tube banks	\$188,427,401	\$118,442,386
SA2	Convective tube banks	\$66,891,332	\$18,731,595
SA3*	Interconnecting piping, cyclones, refractory etc.	\$85,000,000	\$85,000,000
SA4	Tubular oxidant pre-heater	\$31,572,263	\$37,298,332
SA5	Rest of the CFB (Soot blowers, ducts, feeders, fans, structural)	\$25,882,768	\$25,881,783
	Total calculated CFB cost	\$397,773,764	\$285,354,096
	CFB cost from STEAMPRO	\$407,829,000	\$275,026,300
	% Difference	-2.5%	+3.8%

* Estimated based on difference between STEAMPRO data and calculated cost from developed model

Results

Performance Summary

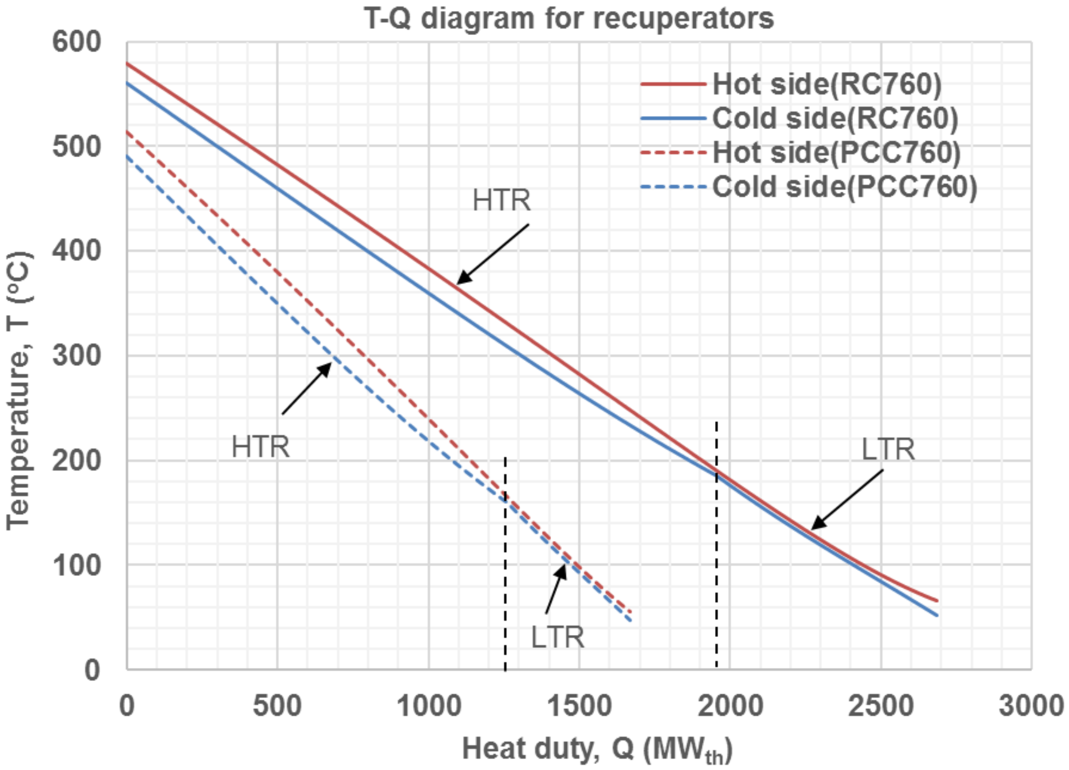
- **Nomenclature for the cases going forward:**
  - RC760 – Recompression cycle without reheat
  - RhtRC760 – Recompression cycle with reheat
  - PCC760 – Partial cooling cycle without reheat
  - RhtPCC760 – Partial cooling cycle with reheat
- **All cases have same coal, limestone and oxygen flow rates**
- **All the CFB designs use tubing outer diameters of 2.0"**
  - IN740H for the furnace radiative tube banks
  - TP347 for convective tube banks
- **RhtPCC760 case offered highest plant efficiency**
  - 2.55 percentage points higher than a reference AUSC Rankine plant which has a net plant efficiency of 36.9%

Parameter	RC760	RhtRC760	PCC760	RhtPCC760
Net plant efficiency (HHV %)	38.64%	38.37%	38.03%	39.45%
Cycle efficiency (%)	51.99%	52.64%	51.80%	53.61%
Cycle specific power (kJ/kg)	160.3	164.8	216.6	233.1
sCO_2 flow rate (kg/s)	4,353.5	4,304.5	3,221.7	3,224.8
Power Generation Summary (MW_e)				
Turbines gross power	937.3	933.9	942.6	955.1
Main compressor power	-116.1	-116.4	-81.2	-78.5
Boost compressor power	--	--	-62.6	-60.4
Bypass compressor power	-97.0	-97.2	-86.3	-82.9
Generator losses	-10.9	-10.8	-10.7	-11.0
Other auxiliaries	-150.6	-150.6	-148.0	-147.8
Net power plant output	562.7	558.8	553.9	574.6
Power Cycle Heat Duties (MW_{th})				
CFB thermal input	1,106.2	1,106.2	1,111.3	1,111.3
HTR duty	1,953.9	2,464.0	1,263.0	1,677.9
LTR duty	730.8	732.3	406.2	391.8
Main Cooler duty	489.6	490.6	198.2	191.6
MC Intercooler duty	138.9	137.2	165.0	159.5
Pre-Cooler duty	0.0	0.0	94.8	91.6
BC Intercooler duty	0.0	0.0	177.6	171.3

Results

Performance Summary, Cont'd

- **sCO_2 mass flow rate of partial cooling cycles (PCC760, RhtPCC760) is ~25% lower than the recompression cycles (RC760, RhtRC760)**
  - Results in lower recuperator duties. For example, PCC760 case recuperation duty is ~38% lower than RC760 case
- **Larger turbine pressure ratio in partial cooling cycles reduces the turbine outlet temperature**
  - Reduces high pressure HTR outlet temperature, thereby increasing the driving force within CFB and reducing the CFB heat transfer area requirements



Results

Performance Summary, Cont'd

- **CFB design summary for all four cases**
  - Total CFB sCO_2 pressure drop is lower for partial cooling cycles compared to their recompression cycle counterparts.
  - sCO_2 pressure drop is significantly higher for the reheat cases compared to non-reheat cases due to increased fluid velocities
  - Due to larger driving forces, CFB cost is lower for the partial cooling cycles compared to their recompression counterparts
  - CFB costs are lower for the reheat cases compared to non-reheat cases due to lower design pressure for reheat tube banks

	RC760	RhtRC760	PCC760	RhtPCC760
CO_2 pressure drop breakdown				
Primary heater (kPa)	999	2,092	719	1,367
Reheat heater (kPa)	-	678	-	376
Economizer (kPa)	49	132	79	55
Total pressure drop (kPa)	1,048	2,902	798	1,798
Cost breakdown (x$1000)				
SA1	$505,267	$467,863	$460,723	$407,875
SA2	$21,561	$38,868	$17,134	$25,624
SA3	$85,000	$85,000	$85,000	$85,000
SA4	$3,101	$3,101	$4,351	$4,351
SA5	$30,034	$30,004	$30,277	$30,277
Total CFB cost	$644,963	$624,865	$597,485	$553,126

Results

Economic Summary

- **On $/kWe basis, TPC of RhtPCC760 case is the lowest**
- **CFB & Accessories capital cost is nearly 50% of the TPC and is significantly higher than entire sCO_2 power block**
  - Highlights the importance of need to focus R&D efforts on development of the coal-fired heat sources
- **sCO_2 power block TPC of partial cooling cycles is lower compared to recompression cycles:**
  - Recuperator costs are significantly lower due to reduction in recuperation duty as well as maximum temperature
  - Main compressor, system piping TPCs are slightly lower due to reduction in cycle mass flow rate
  - Cooler costs are higher since more coolers, compressor intercoolers are needed
  - Boost compressor is a high volumetric flow machine and contributes significantly to the TPC

Cost Account Description	RC760	RhtRC760	PCC760	RhtPCC760
Capital Costs (TPC, x$1000)				
Coal & Sorbent Handling	53,718	53,718	53,718	53,718
Coal & Sorbent Prep and Feed	28,782	28,782	28,782	28,782
Feedwater & Miscellaneous BOP	28,143	28,166	25,902	25,636
CFB & Accessories	1,153,474	1,129,007	1,095,709	1,042,365
Flue Gas Cleanup & Piping	21,871	21,871	20,965	20,965
CO_2 Removal & Compression	204,281	204,281	204,281	204,281
FG Recycle, Ductwork & Stack	30,105	30,105	30,105	30,105
sCO_2 Power Cycle	436,954	548,516	395,824	469,929
Cooling Water System	57,525	57,581	57,885	56,930
Ash & Spent Sorbent Handling	34,372	34,372	34,372	34,372
Accessory Electric Plant	110,851	110,833	110,143	110,210
Instrumentation & Control	32,241	32,241	32,166	32,161
Improvement to Site	19,053	19,200	18,868	18,899
Buildings & Structure	72,866	73,051	72,653	72,645
Total Plant Cost (TPC)	2,284,236	2,371,724	2,181,374	2,200,999
Total Plant Cost ($/kWe)	4,059	4,244	3,938	3,831
sCO_2 Power Cycle Cost Breakdown (TPC, x$1000)				
Main Compressor	58,274	58,307	43,362	42,974
Bypass Compressor	46,011	46,042	42,113	41,647
Boost Compressor	-	-	35,480	47,865
High Temperature Recuperator	88,306	161,122	48,358	82,294
Low Temperature Recuperator	78,912	79,040	53,733	52,183
Coolers (Including intercoolers)	30,489	30,535	46,971	45,762
Turbines	81,952	81,786	82,208	82,812
System Piping	46,291	84,978	37,047	67,814
System Foundations	6,718	6,706	6,552	6,579

Results

Economic Summary, Cont'd

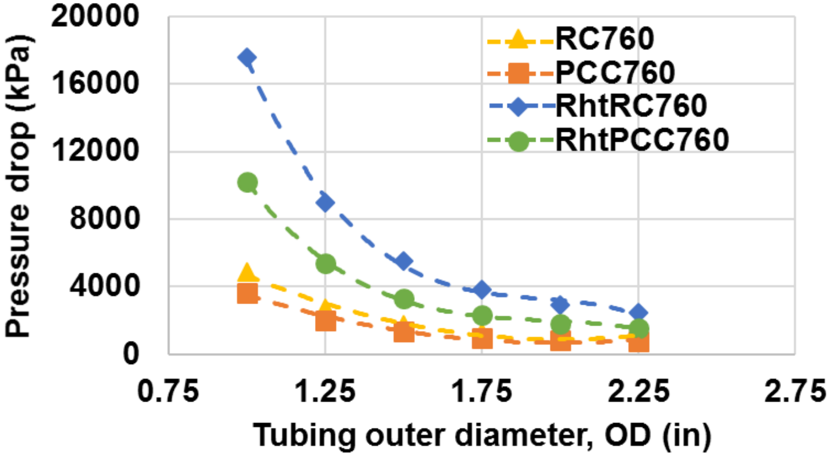
- **RhtPCC760 case had the lowest COE**
  - COE w/o T&S is RhtPCC760 case is 6% higher than reference AUSC Rankine plant which has a COE w/o T&S of 125.7 $/MWh
- **The higher COE for RhtPCC760 case is primarily due to significant increase in the CFB cost relative to reference AUSC Rankine plant ($1,042.3M vs $885.1M)**
  - Turbine inlet temperature of 760°C might not be economical for sCO_2 power cycles with oxy-coal CFB heat sources

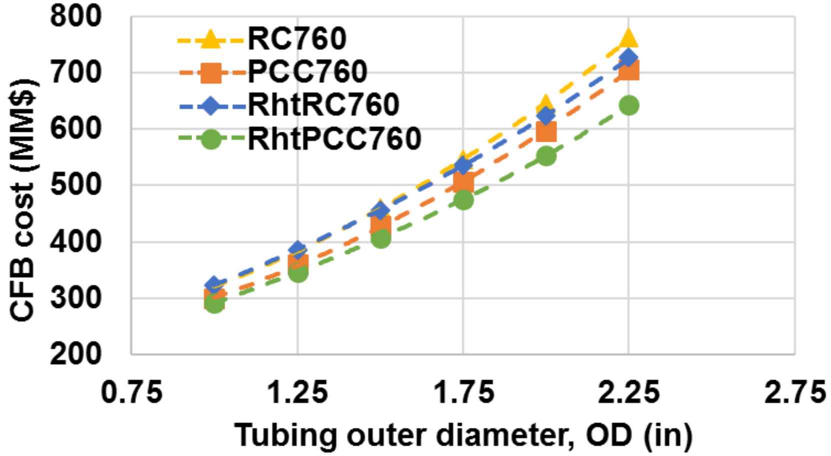
	RC760	RhtRC760	PCC760	RhtPCC760
Operating & Maintenance Costs ($1,000/yr.)				
Fixed O&M	73,369	75,815	70,466	53,718
Variable O&M	56,572	57,425	55,625	55,687
Fuel	108,799	108,799	108,799	108,799
COE breakdown ($/MWh)				
Capital	82.7	86.4	80.2	78.0
Fixed O&M	17.5	18.2	17.1	16.6
Variable O&M	13.5	13.8	13.5	13.0
Fuel	26.0	26.1	26.4	25.4
COE (without T&S)	**139.7**	**144.6**	**137.2**	**133.1**
T&S	7.4	7.5	7.6	7.3
COE (with T&S)	**147.1**	**152.1**	**144.8**	**140.3**

Results

Sensitivity Analysis to CFB Tube Diameter

- **Investigated impact of CFB tubing diameter on sCO_2 pressure drop, CFB cost for all four cases**
  - Tube diameter is assumed to be the same for all tube banks
  - Main and reheat heater tube banks are made of IN740H
  - Economizer tube bank is made of TP347 stainless steel
- **Decreasing tube diameter:**
  - Increases the sCO_2 pressure drop due to higher fluid velocities in tube banks
  - Decreases CFB cost since smaller tubes require thinner walls resulting in lower material costs
- **Reheat cases (RhtRC760, RhtPCC760) saw a significant increase in pressure drop for smaller tubes compared to non-reheat cases**

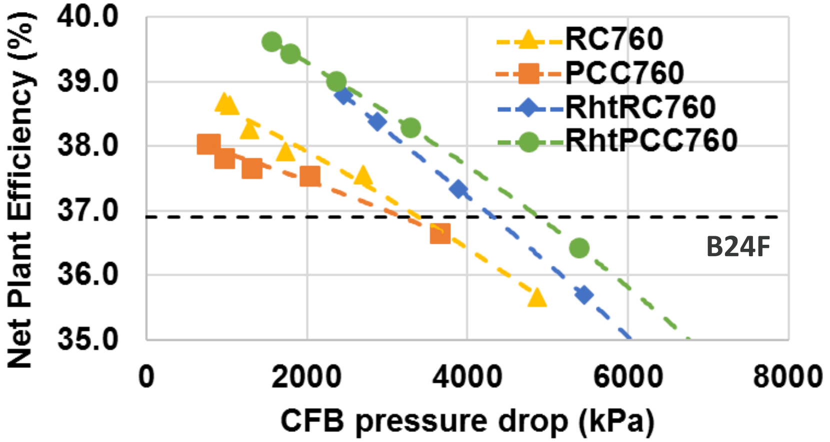


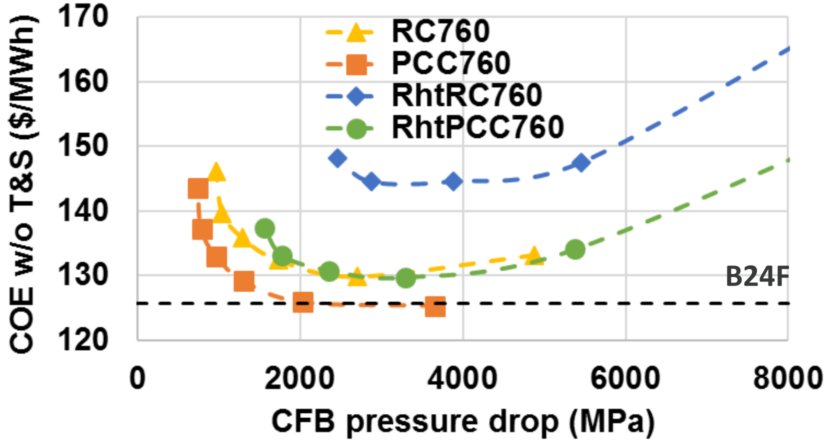


Results

Sensitivity Analysis to CFB Tube Diameter, Cont'd

- **CFB sCO_2 pressure drop vs cost dependency data from previous slide is used to understand the impact on net plant efficiency and COE**
- **Plant efficiency decreases significantly with increasing CFB sCO_2 pressure drop**
  - Out of the four cases, RhtPCC760 case offered highest plant efficiency for wide range of sCO_2 pressure drops
- **Due to opposing trends of CFB pressure drop vs cost, COE presented a minimum for each of the cases**
  - Overall, partial cooling cycles have lower COEs than their recompression cycle counterparts and appear to be better suited for coal-fired CFB heat sources

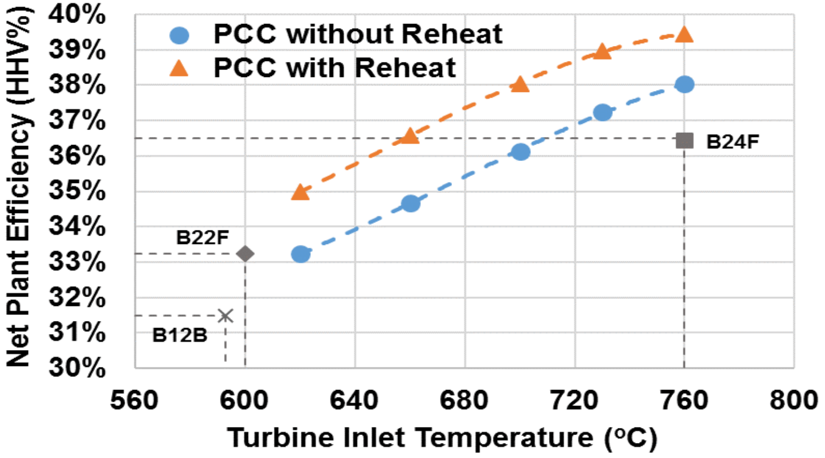


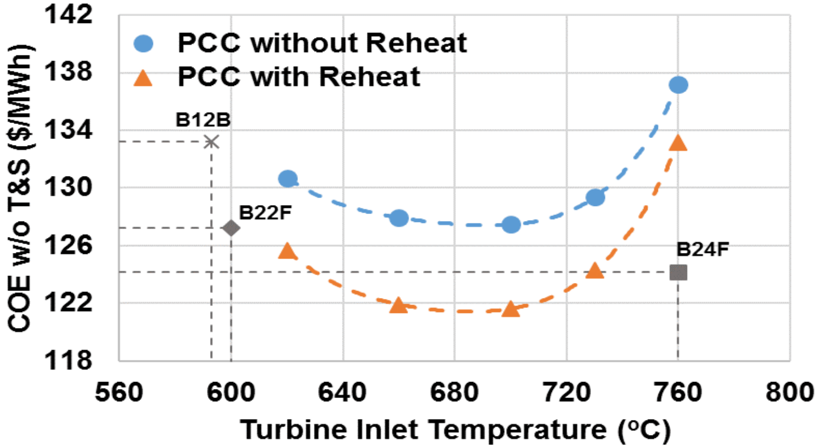


Results

Sensitivity Analysis to Turbine Inlet Temperature

- **Sensitivity analysis to the turbine inlet temperature (TIT) was conducted for partial cooling cycles (PCC) with and without reheat**
- **Plant efficiency increased almost linearly with the TIT**
    - 4.5 – 5 percentage points increase going from TIT of 620°C to 760°C
- **COE exhibited a minimum for TIT ~700 °C if IN740H is mainly used for CFB tubing material**
- **At TIT of 700 °C,**
    - Net plant efficiency of PCC with reheat is 1.5 percentage points higher than reference AUSC steam plant (B24F)
    - COE of PCC with reheat is 2% lower than reference AUSC steam plant (B24F)





Summary and Conclusions

- **This study presented the techno-economic analysis (TEA) results of partial cooling and recompression Brayton cycles with and without turbine reheat using oxy-coal CFB as the heat source**
  - A simplified CFB design tool was developed to improve the accuracy of sCO_2 pressure drop and CFB capital cost estimates – Allows user to capture impact of turbine inlet temperature, pressure, pressure drop, choice of reheat/non-reheat on CFB capital cost
- **Partial cooling cycles have lower mass flow rate, lower recuperator costs and CFB costs than the recompression cycles**
  - Partial cooling cycles require additional coolers, a boost compressor to accommodate higher pressure ratios but these are generally offset by lower recuperator, CFB costs

Summary and Conclusions, Cont'd

- **Reduction in COE possible when CFB pressure drop vs cost impacts are considered by using smaller tubing diameter for CFB**
  - Given the uncertainty in developed CFB model, a more detailed CFB design study should be undertaken to validate these conclusions
  - The study highlights the importance of focusing R&D efforts on development/design of coal-fired heat sources
- **Sensitivity analysis with respect to turbine inlet temperature was conducted for partial cooling cycles**
  - Optimum turbine inlet temperature appears to be around 700 °C, without considering CFB tubing material changes
  - At TIT of 700 °C, net plant efficiency of partial cooling cycle with reheat is 1.5 percentage points higher and COE is 2% lower than reference oxy-CFB steam Rankine plant (B24F) with turbine inlet temperature of 760 °C

Future Work

- **Work in this area is focused on optimizing the plants with respect to other design variables such as cooler temperatures, turbine inlet pressure etc.**
  - Presented at 2021 Turbo Expo
- **Will be conducting a TEA optimization of biomass-fired CFB with sCO_2 power cycles to achieve net-negative CO_2 emissions**
- **Future studies should also focus on reducing the uncertainty in developed CFB model due to several simplifying assumptions**

Acknowledgements

- The authors would like to thank Travis Shultz[1], Richard Dennis[1], Eric Liese[1], and Mark Woods[1,2] for their support and assistance in performing this work.

[1] National Energy Technology Laboratory

[2] NETL Support Contractor

QUESTIONS/ COMMENTS

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@NationalEnergyTechnologyLaboratory

CONTACT:
Nathan T. Weiland
Nathan.Weiland@netl.doe.gov