TECHNICAL AND ECONOMIC EVALUATION OF SUPERCRITICAL OXY-COMBUSTION FOR POWER GENERATION

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ABSTRACT

Coupling supercritical carbon dioxide power cycles with advanced oxy-combustion offers a path to achieve efficient power generation with integrated carbon capture for base load power generation. Tailoring the sCO2 cycle for fossil power generation is a challenge with respect to cycle layout and thermal integration. For example, sCO2 cycles tailored for high efficiency, such as the recompression cycle, typically utilize a high degree of recuperation leading to a narrow temperature change across the thermal input device. This narrow window may be acceptable for waste heat and nuclear applications, however it is at odds with traditional coal and natural gas fired supercritical steam cycles.

Supercritical carbon dioxide power cycles integrating coal fired oxy-combustion were examined by Southwest Research Institute and Thar Energy L.L.C. under DE-FE0009593 to meet the target goal of 90% CO_2 removal at no more than a 35% increase in cost of electricity (COE) as compared to a Supercritical Pulverized Coal Plant without CO_2 capture. Under this project, an indirect supercritical oxy-combustion cycle was developed that provides 99% carbon capture with a 37.9% HHV plant efficiency (39.3% LHV plant efficiency). This cycle achieves a predicted COE of $121/MWe with no credits taken for the additional 9% of carbon capture, and represents a 21% reduction in cost as compared to supercritical steam with 90% carbon capture ($137/MWe).

Initial evaluations of direct fired supercritical oxy-combustion cycles using the recompression closed Brayton cycle indicate that turbine inlet conditions on the order of 1,220 C at 290 bar with power block thermal efficiencies near 64% would enable plant efficiencies exceeding 52% for fuel-to-bus bar efficiency with inherent carbon capture exceeding 99% of generated CO2. These natural gas or syngas direct fired sCO2 still face significant technology development needs such as flue gas cleanup in a closed cycle in addition to thermal management issues such as turbine blade and shaft seal cooling and corrosion associated with the products of combustion.

Additional analysis of the CPOC cycle with recuperation shows promise for fossil fired sCO2 cycles. The recuperated CPOC cycle with a turbine inlet temperature of 1200 C achieves efficiencies on par with the recompression cycle, but has a thermal input window on the order of 1000 C with an inlet temperature near 200 C, as compared to the recompression cycle which has a thermal input window on the order of 250 C and a combustor inlet temperature near 1000 C. This leads to simpler combustor designs, and more efficient usage of fossil based thermal input with the recuperated CPOC cycle. The recuperated CPOC also produces greater power per kg of mass flow, by a factor of 4, and utilizes significantly less recuperation than recompression based cycles.

INTRODUCTION

High cycle efficiency at moderate turbine inlet temperature, compact turbo-machinery, and compatibility with dry cooling are some of the characteristics of supercritical CO2 (sCO2) power cycles that motivate interest in these cycles from a range of power generation areas. These cycle characteristics are due to the physical properties of supercritical CO2, specifically high fluid density, low viscosity, and high heat capacity at pressures above 74 bar at temperatures above 31 C. These characteristics allow the closed Brayton cycle to be effective with simplified cycle layouts for some applications such as waste heat recovery or geothermal power, or to be optimized to achieve performance characteristics and efficiencies suitable for large scale power generation. sCO2 power cycles are being considered for next generation utility scale nuclear and fossil fuel power generation (500 to 1,000 MWe), modular nuclear power generation (300 MWe), solar-thermal power generation (10 to 100 MWe), shipboard propulsion and house power (1, 10, and 100 MWe), geo-thermal power (1 to 50 MWe), and industrial scale waste heat recovery (1 to 10 MWe).

Coupling sCO2 cycles with advanced oxy-combustion offers a path to achieve efficient power generation with integrated carbon capture for base load power generation. Tailoring the sCO2 cycle for fossil power generation is a challenge with respect to cycle layout and thermal integration. For example, sCO2 cycles tailored for high efficiency, such as the recompression cycle, typically utilize a high degree of recuperation leading to a narrow temperature change across the thermal input device. This narrow window acceptable for waste heat and nuclear applications, however it is at odds with traditional coal and natural gas fired supercritical steam cycles.

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The overall technical readiness of the supercritical oxy-combustion cycle is estimated at TRL 2, Technology Concept, due to the maturity level of the supercritical oxy-combustor for solid fuels, and several critical supporting components, as identified in the accompanying Technical Gap Analysis. The supercritical oxy-combustor for solid fuels operating at pressures near 100 atm is a unique component of the supercritical oxy-combustion cycle. In addition to the low TRL supercritical oxy-combustor, secondary systems were identified that would require adaptation for use with the supercritical oxy-combustion cycle. These secondary systems include the high pressure pulverized coal feed, high temperature cyclone, removal of post-combustion particulates from the high pressure cyclone underflow stream, and micro-channel heat exchangers tolerant of particulate loading.

Initial analysis of direct fired oxy-combustion cycles utilizing the recompression closed Brayton cycle indicate that turbine inlet conditions on the order of 1,220 C at 290 bar would enable power block thermal efficiencies near 64%. Utilizing current generation air separation methods, it is anticipated that 64% cycle efficiency would enable direct fired oxy-combustion to achieve plant efficiencies exceeding 52% for fuel-to-bus bar efficiency with inherent carbon capture exceeding 99% of generated CO2. The natural gas or syngas direct fired sCO2 oxy-combustion cycle eliminates the challenge of pulverized coal injection and combustion at elevated temperatures and pressures, while facing similar challenges to the indirect oxy-combustion cycle such as narrow temperature window for thermal input with the recompression cycle and flue gas cleanup, and adds challenges associated with the high firing temperatures such as blade cooling, enhanced thermal management, and corrosion associated with the products of combustion.

COAL FIRED sCO2 OXY-COMBUSTION CYCLES

Two concepts for supercritical oxy-combustion cycles were evaluated to address the cost of electricity through increased cycle efficiency. These cycle concepts are the Cryogenic Pressurized Oxy-Combustion Cycle (CPOC) and the Advanced Supercritical Oxy-Combustion Cycle. Both cycle concepts seek to maximize net plant efficiencies by maximizing the efficiency of the power block, minimizing power loss due to accessory systems, and increasing combustion efficiencies. Both cycle concepts leverage recent advances in supercritical CO_2 (sCO_2) power cycles and current development efforts[1] for CO_2 turbo-machinery by utilizing sCO_2 as the working fluid for the power block. In the direct-fired configurations, the sCO_2 working fluid is the flue gas and includes products of combustion. In the indirect cycle configurations, the flue gas and products of combustion are contained within the combustion loop, and high quality CO_2 is used as the working fluid in the power block.

The CPOC cycle is a trans-critical power cycle that leverages recent advances in iso-thermal compression to minimize recompression costs, shown in Figure 1, while the advanced supercritical oxy-combustion cycle, shown in Figure 2, is based on the recompression cycle and maintains supercritical pressures throughout the system.

[1] DE-EE0005804, "Development of a high efficiency hot gas turbo-expander and low-cost heat exchangers for optimized CSP supercritical CO_2 operation," Southwest Research Institute, General Electric Global Research, and Thar Energy

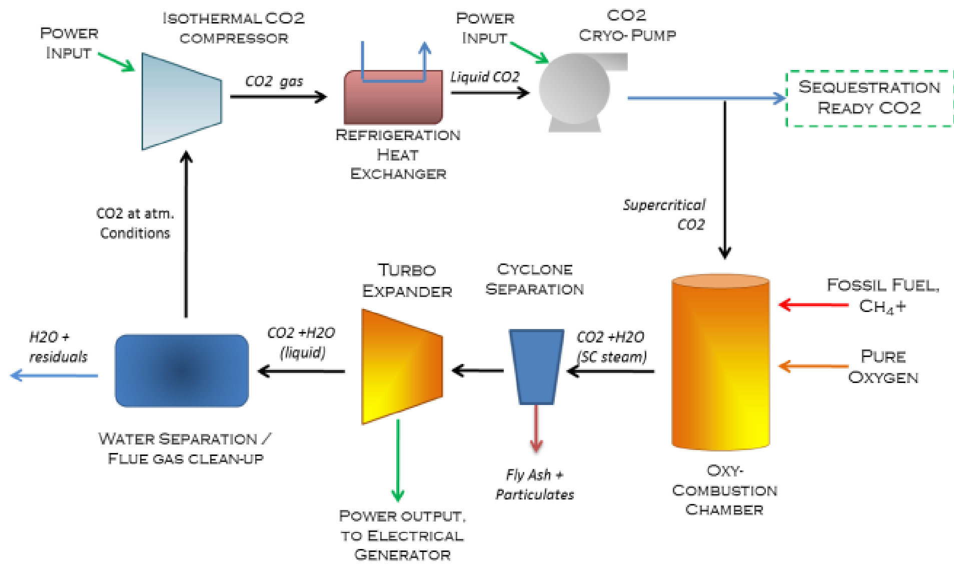

Figure 1. Direct fired CPOC concept

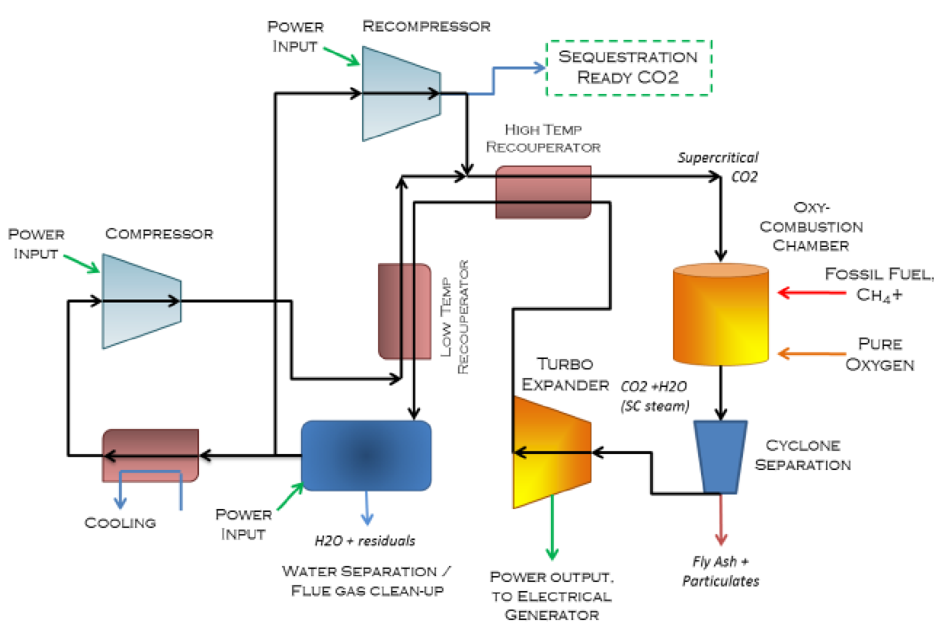

Figure 2. Direct Advanced Supercritical Oxy-combustion Cycle based on the recompression cycle

Initial evaluation of the CPOC and the supercritical oxy-combustion cycle focused on maximizing thermal efficiency of the power blocks. Cycle models were implemented using Aspen Plus for the respective power blocks, the Cryogenic Pressurized Oxy-Combustion Cycle (CPOC), shown in Figure 3, and the supercritical CO2 (sCO2) recompression cycle, shown in Figure 5. These models were used to perform an initial comparison of the two cycle configurations to assess thermal efficiency, shown in Figure 4 and Figure 6, and the impact of component performance on the overall cycle. This initial analysis showed that the recompression cycle achieved higher thermal efficiencies, near 47% at 650 C and 290 atm, with a similar level of component maturity as the CPOC cycle achieving 38% thermal efficiency for reasonable loop pressures. Based on this analysis, the recompression closed Brayton cycle was selected for further cycle optimization and integration with the combustion system. Further evaluation of the CPOC cycle after the completion of the coal fired oxy-combustion study indicate that cycle efficiencies close to the recompression cycle are achievable with the inclusion of recuperation, as described in a later section.

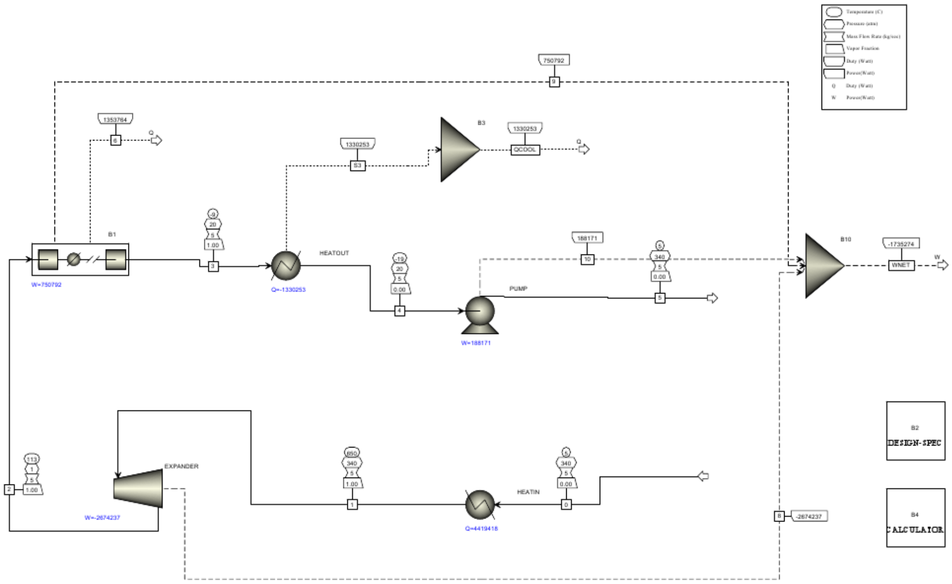

Figure 3. Aspen Plus layout of the CPOC power block

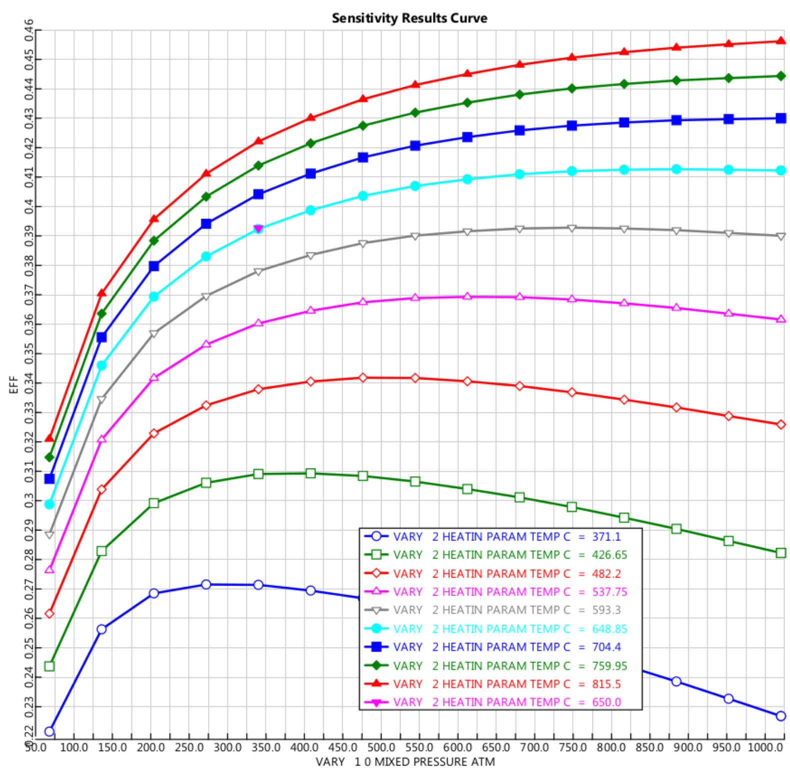

Figure 4. CPOC efficiency as a function of temperature and pressure

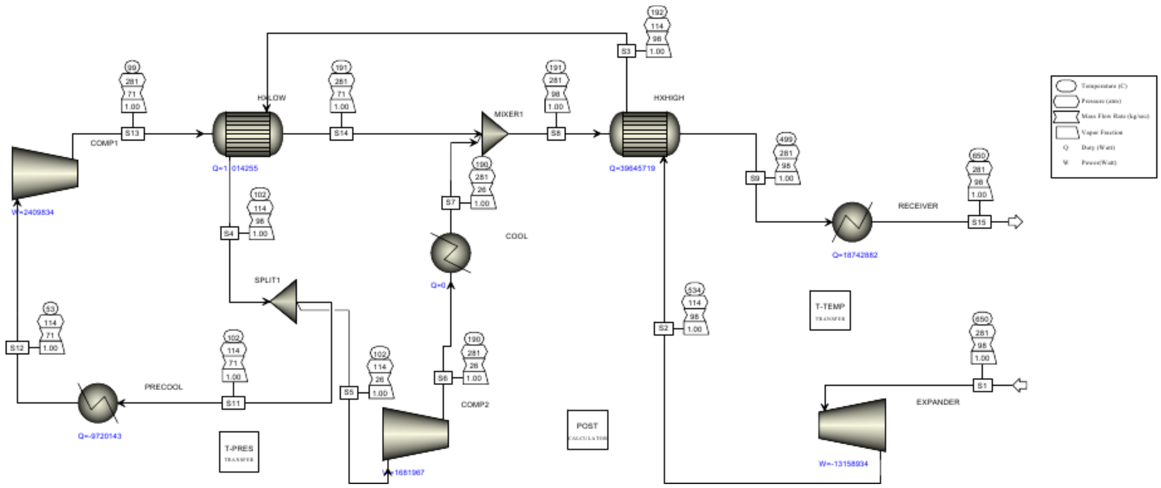

Figure 5. Aspen Plus layout of the sCO2 recompression cycle

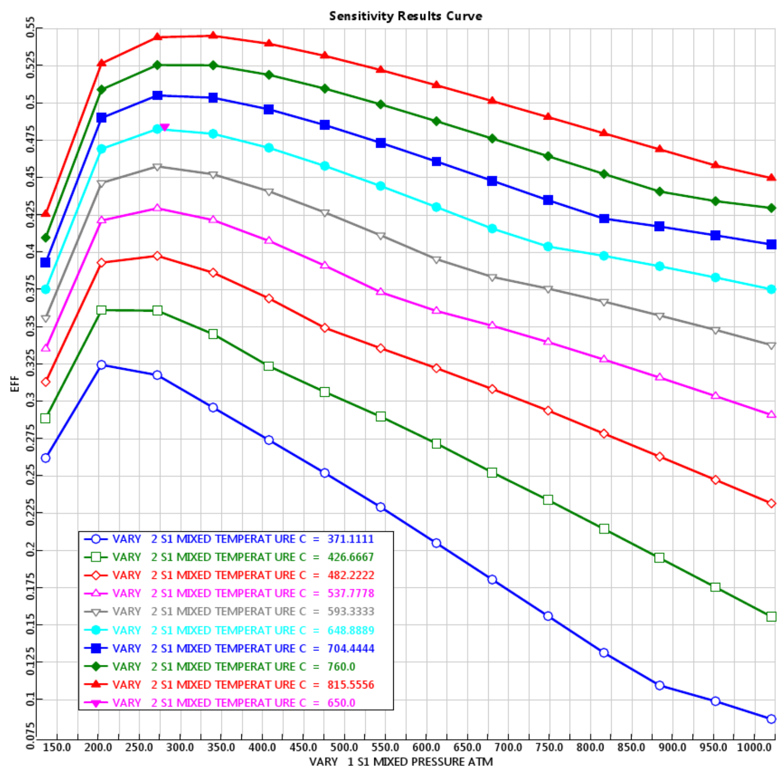

Figure 6. sCO_2 recompression efficiency as a function of temperature and pressure

Cycle Optimization for High Net Efficiency and Low Cost

Initial cycle evaluation of the supercritical oxy-combustor and the sCO_2 power block using simplified cycle models indicated that an indirect cycle configuration that allowed the combustion and power loops to operate at differential pressures would be advantageous, as the increase in power block efficiency was greater than the losses associated with the heat exchanger interfacing the two loops. As an added benefit, isolating the post-combustion to the combustion loop minimized wear and fouling of the turbomachinery. This comes at the risk of increased fouling of the less expensive interface heat exchangers. The reduced operating pressure on the combustion side also enables greater re-use of commercially available technologies for flue gas cleanup, decreasing economic and technical risk for developing the supercritical oxy-combustor.

The use of a supercritical CO_2 power block enables high thermal efficiencies, near 48% for 650°C turbine inlet temperature, but also poses a challenge for the cycle design due to the narrow temperature range for the thermal input, as shown in the temperature-enthalpy diagrams in Figure 7 for a 700°C sCO_2 power cycle and the supercritical oxy-combustion loop. For the current cycle configuration, shown in Figure 8, the temperature difference between the power block outlet to inlet is only 196 C. This has two significant impacts on the cycle design. First, the transfer 1.2 GW of thermal energy from the combustor to the power block across a narrow temperature range requires a significant mass flow of CO2, roughly 4929 kg/s of flue gas. Second, to minimize the amount of fuel and thermal input at the combustor, maximizing cycle efficiencies, the temperature rise in the combustor should be as close as the HX allows, which requires a recycle CO2 temperature near 454°C.

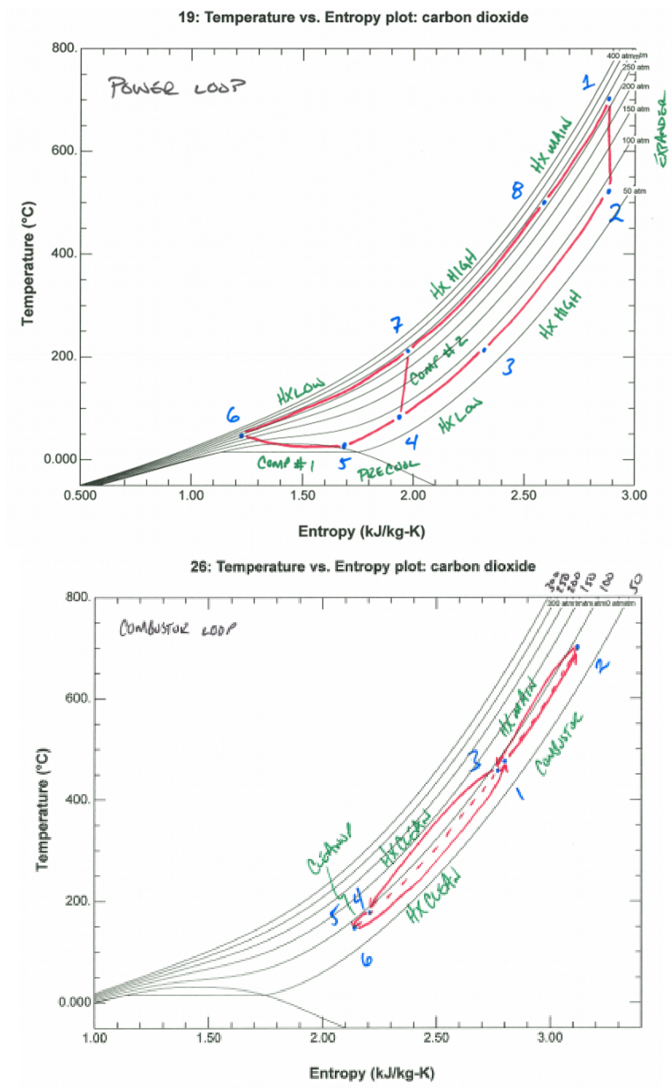

Figure 7. Temperature-entropy diagram for a 700 C recompression power and combustion loops

The elevated temperature of the recycle loop poses challenges for flue gas cleanup, which is typically performed at reduced temperatures and pressure as compared to the proposed cycle conditions. In order to use a conventional wet limestone flue gas desulfurization, and minimize temperatures at the boost pump and the CO2 sequestration stream, a recuperater is incorporated into the supercritical oxy-combustion loop, as shown in Figure 8, to enable cleanup, dewatering, and re-compression at reduced temperatures.

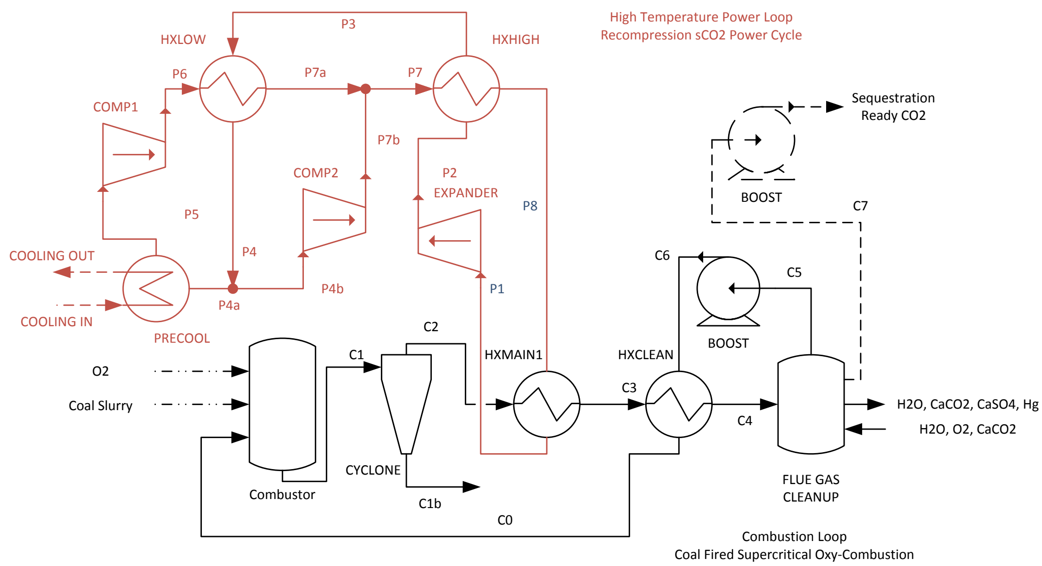

Figure 8. Indirect supercritical oxy-combustion cycle layout with a recompression sCO_2 power block

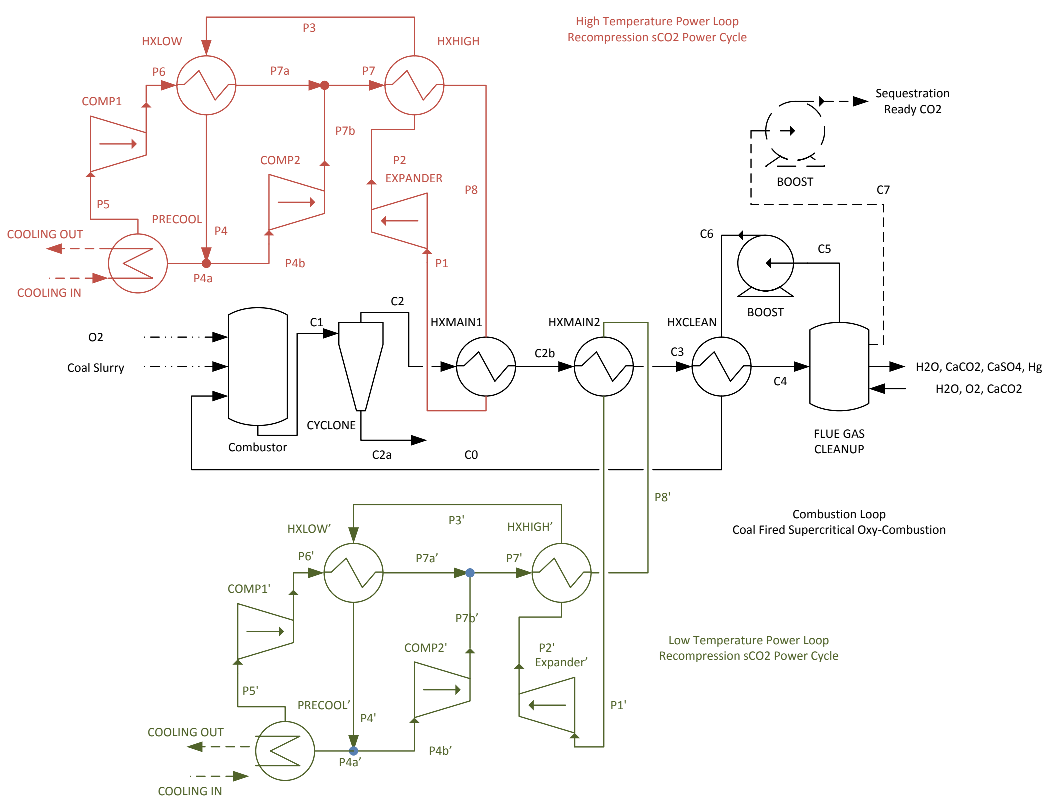

Figure 9. Dual loop oxy-combustion cycle layout with two recompression sCO2 power cycles

As part of the cycle optimization, an alternative configuration was evaluated which places two smaller sCO2 power blocks in series. This configuration doubles the temperature drop across the combustion loop, leading to lower recycle temperatures and a reduced recycle mass flow. This reduction in mass flow comes at the cost of two smaller power blocks, and two smaller heat exchangers for the same net power output. A schematic for this configuration is shown in

Figure **9**. Plant efficiencies for the dual power block configuration were reduced by 1%, impacted by the additional thermal losses associated with the extra heat exchanger, and the loss of power block efficiency for the second power block operating at a lower temperature. Economic analysis of both configurations showed a cost increase of $12/MWe for the dual power block configuration when compared to the single block configuration shown in Figure 8.

This optimized cycle configuration is able to achieve 37.9% HHV plant efficiency (39.3% LHV plant efficiency) with 99% carbon capture for a COE of $121/MWe. This exceeds the stated program objectives of 35% increase in COE, however the supercritical oxy-combustor represents a 21% reduction in COE when compared to current power generation technologies with 90% CO2 capture, while capturing and sequestering 99% of the generated CO2. The selection of 650 as the firing temperature represents a design tradeoff to limit firing temperature in order to use austenitic stainless steels for the high temperature pressure vessels and piping, and to minimize the need for advanced turbomachinery features such as blade cooling.

TECHNOLOGY GAP ANALYSIS

A Technical Gap Analysis of the supercritical oxy-combustion power cycle identified one critical component with a low Technology Readiness Level (TRL). The supercritical oxy-combustor operating at pressures near 100 atm is a unique component to the supercritical oxy-combustion cycle. In addition to the low TRL supercritical oxy-combustor, several secondary systems were identified that are commercially available, but would require adaptation for use with the supercritical oxy-combustion cycle. These secondary systems include the high pressure pulverized coal feed, the high temperature cyclone, the removal of post-combustion particulates from the high pressure cyclone underflow stream, and micro-channel heat exchangers tolerant of particulate loading.

Key findings of the technical gap analysis include:

- Air separation for oxy-combustion is a major cost item, exaggerated by the need to pressurize the O2 stream to nearly 100 bar. While the technology and manufacturing capability to provide oxygen in the quantity required of a 550 MW oxy-combustion power plant, the state-of-the-art for pumping/compression components is not yet up to commercial readiness.
- Particulate removal technology is available, but with the following caveats: Process engineering is required to develop a system for de-pressurization and recovery of solids. Cyclones should be outfitted with replaceable inner jackets, so as to manage abrasion and wear. The particulates that escape from cyclone separation will likely be in a size range of 1-5 microns; the downstream heat exchangers must be capable of handling these particles.
- Cyclones, heat exchangers, air separation units, and flue gas desulfurization systems should be specified as multiple smaller units in parallel. This is advantages for economy of scale and sparing.
- Compact, low cost heat exchangers are a key technology impacting footprint and cost of the supercritical oxy-combustion cycle. Microchannel heat exchangers are currently at a low TRL, but are actively being developed for multiple applications including supercritical CO_2 power cycles. Because it is expected that 1-5 micron may pass through the cyclone separator, heat exchanger sparing and cleaning are important considerations.
- Metals removal, particularly mercury, can occur in the same equipment as used for flue gas desulfurization.
- Desulfurization using limestone slurry with recovery of gypsum byproduct is the preferred flue gas desulfurization method at elevated pressured.

- For slurry handling, conventional progressive-cavity pumps can be used for conveying slurry at low pressure differential into holding tanks. There, the pressurized stream of recycle CO_2 can be used to bring the slurry to pressure. Direct feed of dry pulverized coal would be preferred to maximize plant efficiencies, however direct feed systems at high pressures are at a low TRL.

SUPERCRITICAL OXY-COMBUSTOR

A swirl type supercritical oxy-combustor for solid fuel was developed from initial concept to an advanced design stage as illustrated in Figure 10. The combustor development focused on flow path and combustion optimization using FLUENT and Chemkin to model the flow through the combustor and provide initial assessment of the coal combustion reactions in the flow path. This design effort included initial combustor mechanical layout, initial pressure vessel design, and the conceptual layout of a pilot scale test loop.

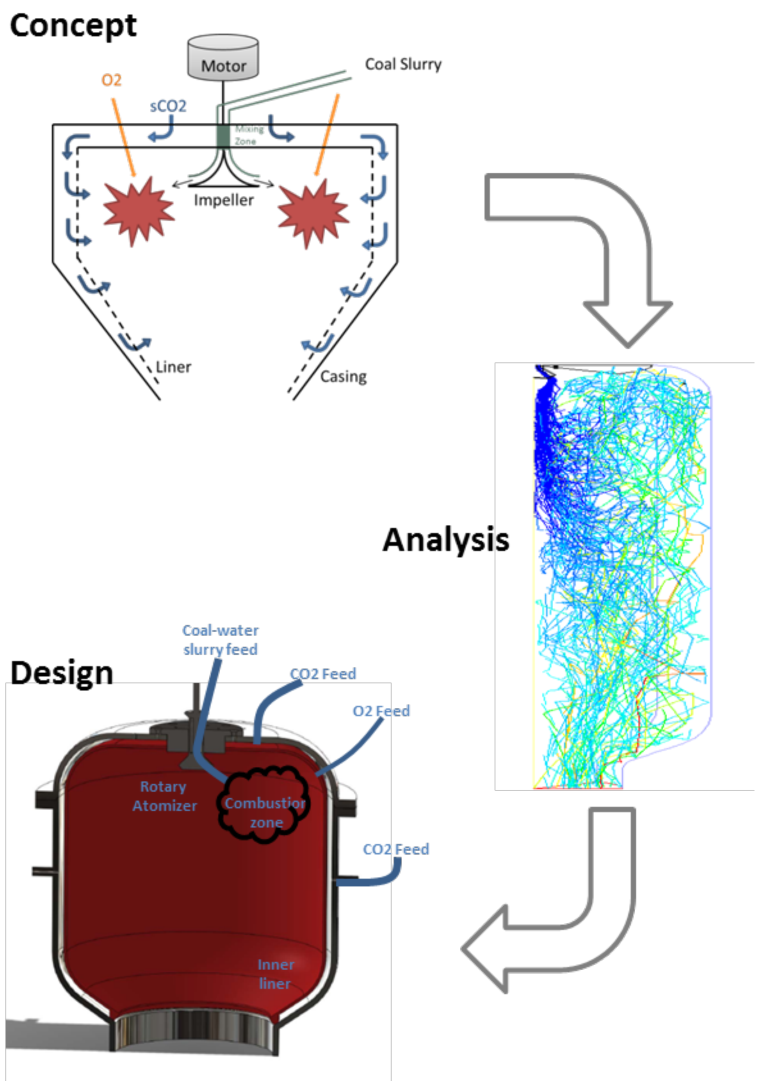

Figure 10. Evolution of the supercritical oxy-combustor design

The supercritical oxy-combustor, shown in Figure 11, injects a coal water-slurry or coal-CO2 slurry located at the top of the combustion chamber. This slurry is dispersed into the combustion zone using a rotary atomizer to break up and evenly distribute the slurry. Diluent CO2 is injected into an annulus formed by the combustor casing and a porous thermal barrier. The CO2 provides cooling to the liner as it flows through into the combustion chamber. The location of the combustion zone within the chamber is controlled by the location of the O2 injectors and mixing of the fuel and oxidizer in the combustion chamber. The hot flue gas, inorganics, and any solid combustion byproducts flow down and out of the combustion chamber into hydrocylones responsible for the hot particulate cleanup.

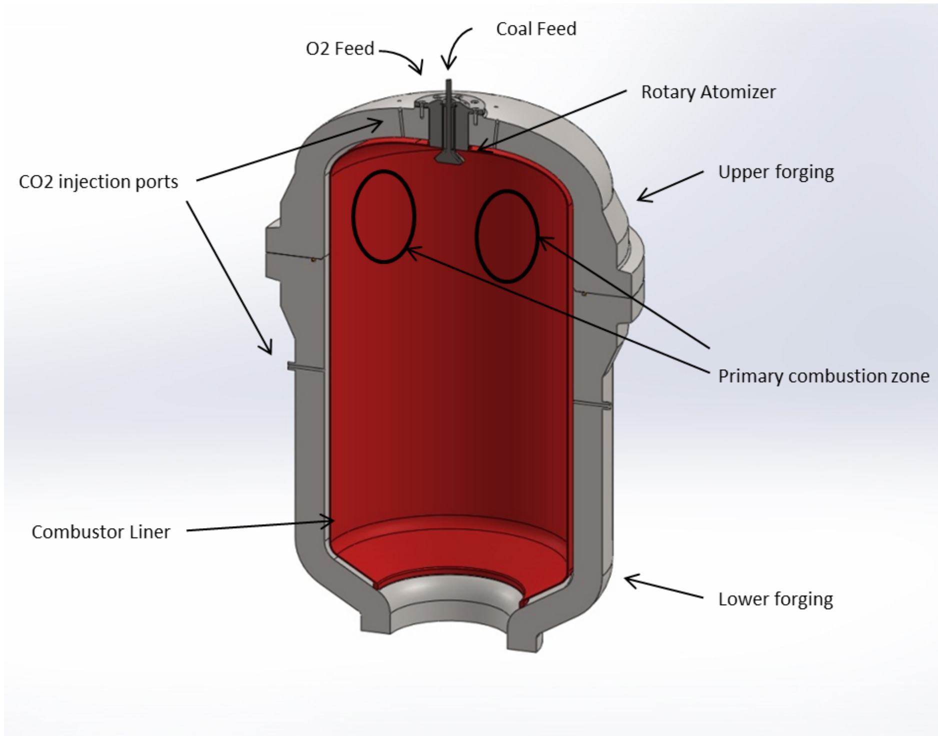

Figure 11. Supercritical oxy-combustor detail

Along with the design of the supercritical oxy-combustor, initial design for a 1 MWth pilot scale test loop for the thermal side of the supercritical oxy-combustion cycle has been initiated. This test loop integrates the scaled supercritical oxy-combustor with the cyclone separator for particulate removal, a compact microchannel recuperator, a water scrubber, and boost compressor in a layout representative of the full scale supercritical oxy-combustion cycle, as shown in Figure 12. A conceptual rendering of the 1 MWth pilot scale test loop is shown in Figure 13. Coal flow rate would be on the order of 0.05 kg/s, with a flue gas recycle rate of 3.4 kg/s for a 1 MWth demonstration.

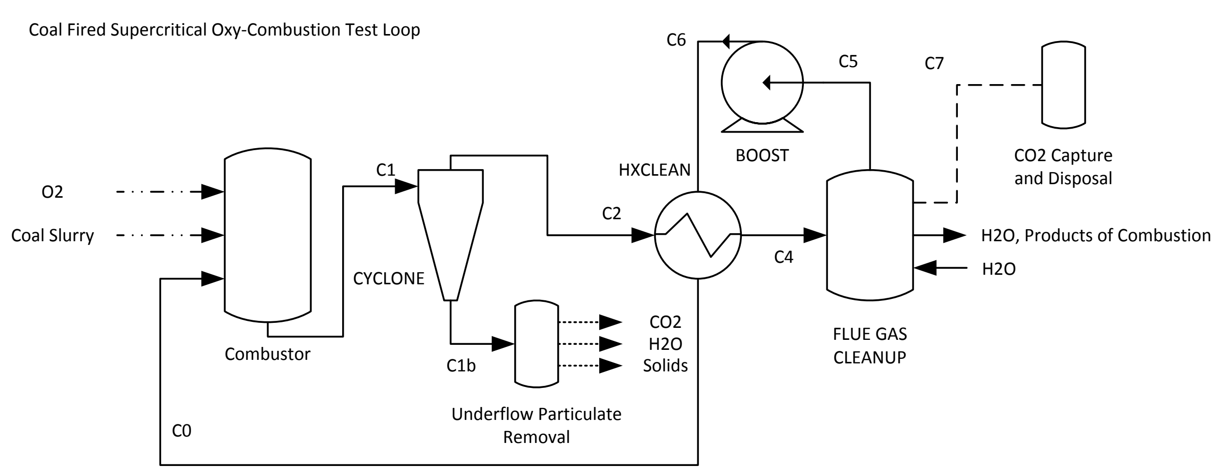

Figure 12. Process layout for a pilot scale supercritical oxy-combustion loop

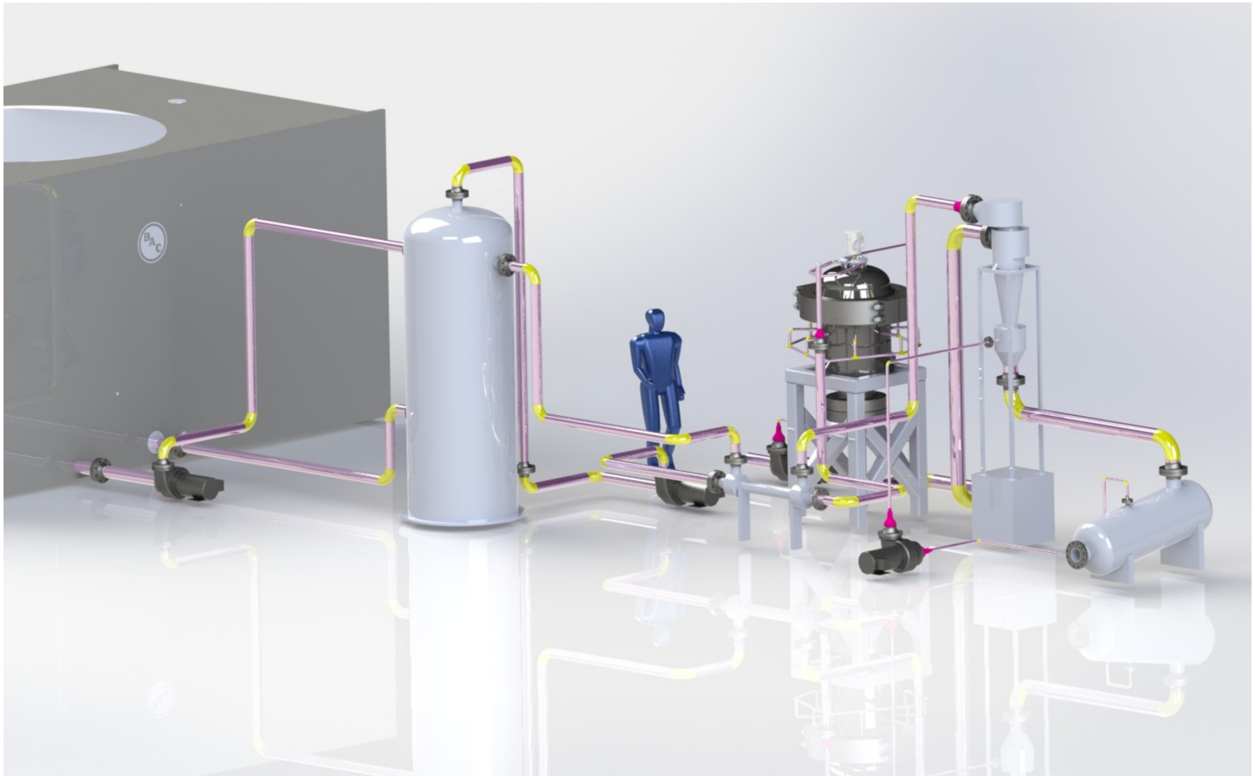

Figure 13. Rendering of a 1 MWth supercritical oxy-combustion test loop concept

RECOUPERATED CPOC

Further analysis of the CPOC cycle revealed that incorporating recuperation enhanced cycle performance significantly. At lower temperatures, the recuperated CPOC cycle efficiencies exceed the efficiency of the recompression cycle, as shown in Figure 16. At a firing temperature of 1200 C, thermal efficiencies for both the Recuperated CPOC and the recompression are 63%.

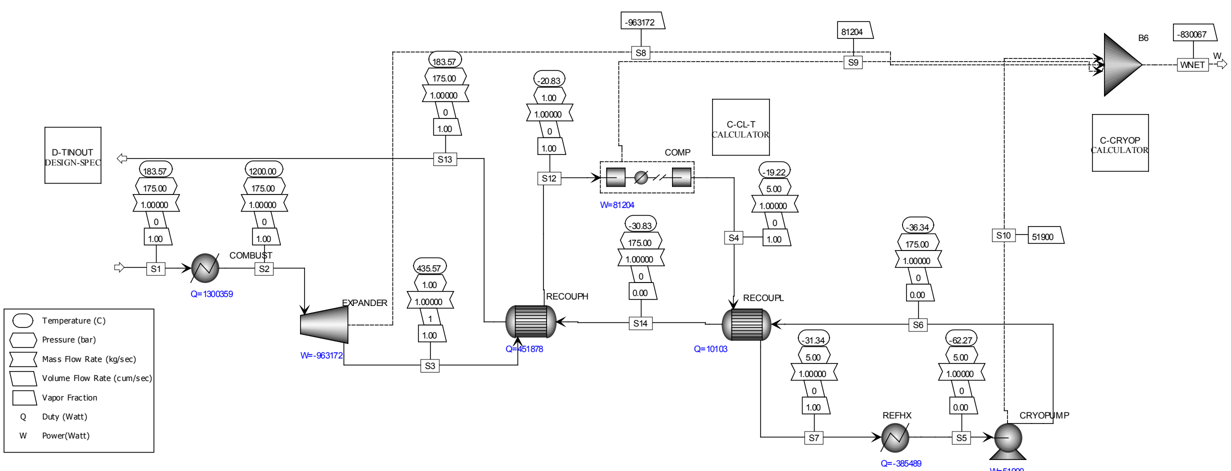

Figure 14: ASPEN Plus process flowsheet for CPOC with recuperation.

Adding recuperation reduces compression power requirements by reducing the inlet temperature at the pump, minimizes refrigeration requirements, and maximizes combustor inlet temperature. When coupled with a reduction in pressure at liquefaction, cycle efficiencies approach those of the recompression cycle.

In addition the advantageous cycle efficiencies, the Recuperated CPOC generates 830 kW/kg net power, as compared to 221 kW/kg for the recompression cycle, and only requires 471 kW/kg of recuperation as compared to 1,151 kW/kg for the recompression cycle. For a nominal 550 MWe power plant, this corresponds to a CO2 flow rate of 662 kg/s and 312 MW of recuperation for the recuperated CPOC as compared to 2488 kg/s CO2 flow and 2,864 MW of recuperation for the recompression cycle. This represents significant reduction in hardware cost.

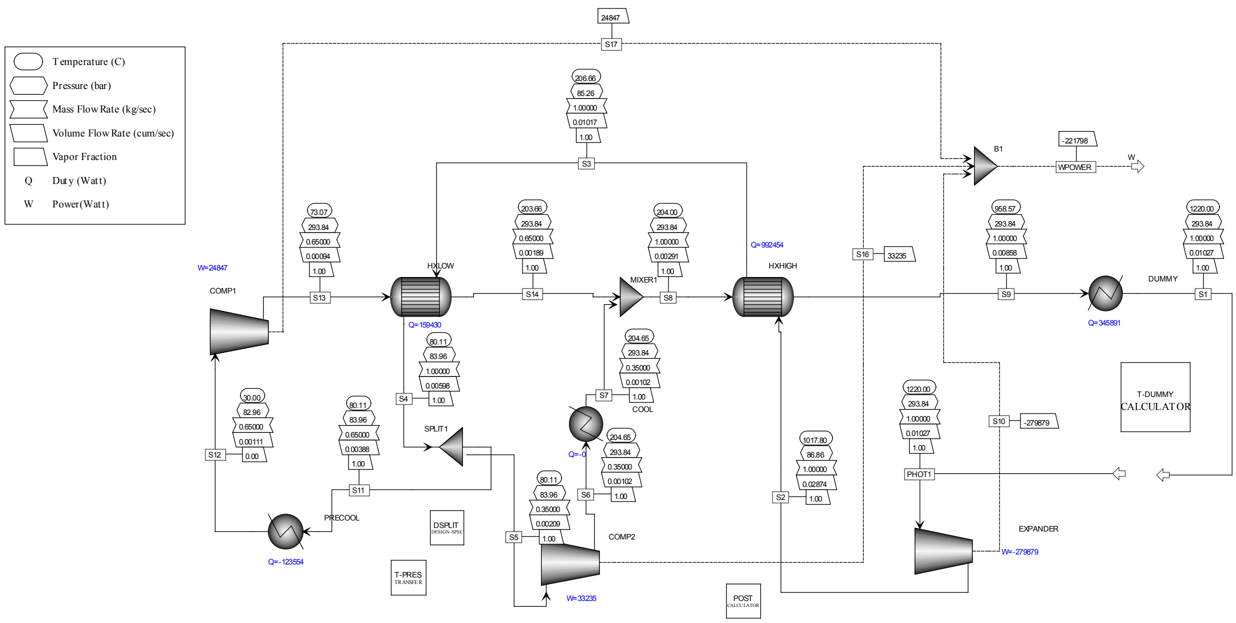

Figure 15. ASPEN Plus process flowsheet for the recompression power block.

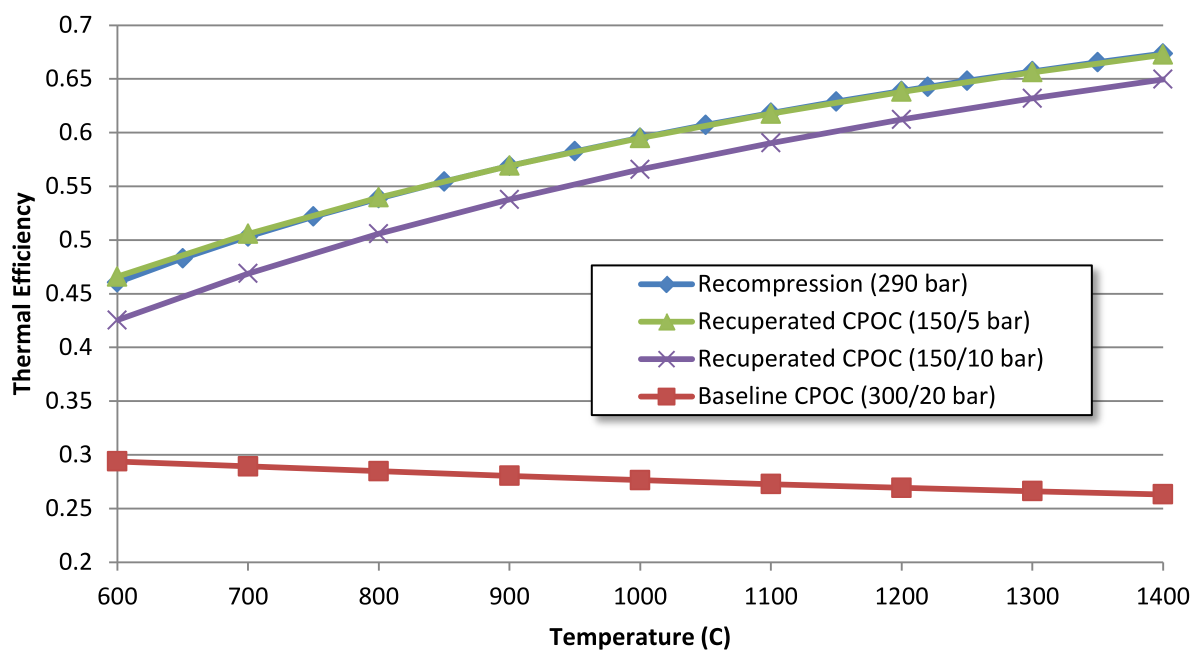

Figure 16. Revised efficiencies for CPOC with recuperation

CONCLUSIONS

sCO2 cycles for fossil based power generation require significant optimization and integration of the power cycle and thermal input system to achieve high plant efficiencies. Two cycles, the CPOC and the Cryogenic Pressurized Oxy-Combustion Cycle (CPOC) and the Advanced Supercritical Oxy-Combustion Cycle were evaluated for coal fired power generation, and an optimized indirect supercritical oxy-combustion cycle was developed under DE-FE0009593. This coal fired cycle faces non-insignificant technology development challenges to achieve a moderate reduction in LCOE as compared to supercritical steam with integrated carbon capture.

Initial evaluations of direct fired supercritical oxy-combustion cycles using the recompression closed Brayton cycle indicate that turbine inlet conditions on the order of 1,220 C at 290 bar with power block thermal efficiencies near 64% would enable plant efficiencies exceeding 52% for fuel-to-bus bar efficiency with inherent carbon capture exceeding 99% of generated CO2. These natural gas or syngas direct fired sCO2 still face significant technology development needs such as flue gas cleanup in a closed cycle in addition to thermal management issues such as turbine blade and shaft seal cooling and corrosion associated with the products of combustion.

Additional analysis of the CPOC cycle with recuperation shows promise for fossil fired sCO2 cycles. The recuperated CPOC cycle with a turbine inlet temperature of 1200 C achieves efficiencies on par with the recompression cycle, but has a thermal input window on the order of 1000 C with an inlet temperature near 200 C, as compared to the recompression cycle which has a thermal input window on the order of 250 C and a combustor inlet temperature near 1000 C. This leads to simpler combustor designs, and more efficient usage of fossil based thermal input with the recuperated CPOC cycle. The recuperated CPOC also produces greater power per kg of mass flow, by a factor of 4, and utilizes significantly less recuperation than the recompression based cycle.

NOMENCLATURE

CPOC = Cryogenic Pressurized Oxy-Combustion Cycle
sCO2 = Supercritical Carbon Dioxide

ACKNOWLEDGEMENTS

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