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Improving Flexibility and Performance of Staged Pressurized Oxy-Combustion

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Abstract

Staged pressurized oxy-combustion (SPOC) is a novel coal combustion power technology being developed by Washington University in St. Louis (WUSTL) that offers the potential to deliver low-carbon power at a reduced cost. Oxy-combustion plants operate by removing most of the nitrogen contained in air prior to combustion, thereby burning fuel in a near-pure oxygen stream instead of air. This combustion produces a flue gas containing primarily carbon dioxide (CO_2) and water vapor that allows relatively straightforward CO_2 capture. First-generation, atmospheric oxy-combustion technology relies on a flue gas recycle (FGR) diluent to reduce the peak temperatures achieved and the resulting high thermal radiation levels that would otherwise occur in a fuel/oxygen only flame. In contrast, by staging the combustion in several steps, SPOC reduces the peak temperatures of combustion without resorting to a high degree of FGR to control flame temperatures. The SPOC process operates by utilizing two or more pressurized boiler modules connected in series to produce fuel staging; hence, only a portion of the fuel is combusted in any given combustion module. Subsequently the thermal energy released at each stage can be captured and removed from the gases prior to subsequent stages, when more fuel is introduced. This allows the SPOC process to operate with minimal FGR, avoiding the associated efficiency losses and additional costs.

While the staging controls the heat release profile in SPOC, operating in a pressurized condition yields a more compact system, reducing modular boiler size and delivering enhanced heat transfer. Additionally, operating at elevated pressures ensures that the latent heat of moisture available from moisture in the fuel and generated by the combustion of the hydrogen content in the fuel can be captured as useful thermal energy for steam turbine integration. This is possible due to elevated dew point from the high partial pressure of the moisture generated in this process, which allows substantial feedwater heater bypassing to be achieved. The inclusion of this thermal energy, normally lost to the atmosphere in traditional combustion processes or to cooling systems in atmospheric oxy-combustion, allows the resultant net efficiency of the SPOC system to be up to 6 percentage points greater than first-generation systems[1].

To begin the process of developing this technology for full-scale application, the Electric Power Research Institute, Inc. teamed up with WUSTL, American Air Liquide, Doosan Babcock, and the U.S. Department of Energy to investigate a practical and workable boiler design concept that would minimize process risks where possible. The SPOC system offers unique process flexibility

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opportunities due to the staged nature of the combustion, making it a prime candidate for future primary energy delivery where the ability to operate at reduced load in an efficient manner and ramp rapidly will be valuable for balancing intermittent renewable electricity generation. The efficiency of traditional coal-fired power plants is lower at reduced loads below the steam temperature control range due to the challenges in balancing the heat pickup between radiative and convective superheater and reheater surface. Introducing additional heating surface for optimal extended controlled low load operation will likely lead to excessive attemperation at high loads, ultimately leading to a poorer overall cycle efficiency. The SPOC process can facilitate the adjustment of fuel firing rates between stages, targeting heat pickup to where it is most needed and potentially can shut down stages for low-load operation, facilitating an increased steam temperature control range on turndown.

The boiler design concept assessment is being carried out to identify the maximum permissible compactness of the SPOC boiler heating surfaces. The assessment will determine the minimum overall height that will deliver appropriate tube operating metal temperatures at full load and achieve rated reheat steam temperatures at low operating loads, balanced against the needs of efficient coal combustion, and the potential resultant slagging and ash environments. The design parameters are being validated by combustion testing in the 100-kWth pressurized combustion test rig at WUSTL. Parameters being investigated include flame stability, fuel burnout, ash composition, radiative heat flux, and temperature profiles. These are being carried out for a range of inlet gas conditions and compositions and at multiple load conditions to investigate combustion stability at reduced load. The results of this testing inform the modeling of the large-scale system, that was sized at 550 MWe to allow direct comparison with the National Energy Technology Laboratory baseline cases for atmospheric oxy-combustion, air firing, and air firing with post-combustion capture.

Keywords: CO_2 capture, pressurized, oxy-combustion, scale-up, pilot testing

1. Introduction

Oxy-combustion facilitates convenient carbon dioxide (CO_2) capture as the fuel is burnt with oxygen rather than using air directly. Flue gas generated from oxy-combustion consists of mainly CO_2 and water and so can be delivered for CO_2 sequestration or utilization with minimal post processing. Carrying out the combustion of fuel directly with oxygen results in very high flame temperatures and unmanageable heat flux levels, hence conventional oxy-combustion systems use a diluent gas to reduce peak temperatures and even out the heat flux intensity to allow boiler tubes to absorb this thermal energy. The diluent gas used is typically flue gas recycle (FGR) that is returned from the boiler outlet to the burner zone in place of combustion air. FGR requires additional auxiliary power to deliver the required volume of gas back to the burners.

Staged pressurized oxy-combustion (SPOC) is a technology being developed by Washington University in St. Louis (WUSTL) that offers higher overall power plant efficiency than is achievable with first-generation atmospheric oxy-combustion. By separating the overall fuel burn into multiple stages, the quantity of FGR needed can be greatly reduced as the resultant flame temperatures for each individual stage are more easily managed due to the lower fuel firing rate. The SPOC system is also pressurized, making the flue gas volume smaller than with conventional atmospheric oxy-combustion, yielding a smaller overall footprint and lower downstream CO_2 compression power requirements. Another benefit of operating at elevated pressure is gas-side heat transfer enhancement, reducing the quantity of boiler bank tubing needed to achieve the required thermal absorption.

As the flue gas produced contains a large component of moisture either directly from the fuel or from the combustion of the hydrogen content, a significant amount of moisture latent heat is available. Pressurizing the process allows the capture of this energy, normally represented by the difference between the gross calorific value (GCV) and the net calorific value (NCV) of the fuel. This energy is normally lost to the atmosphere via the stack in conventional air-fired combustion plants, or to the cooling system for the case of atmospheric oxy-combustion systems. The partial pressure of the moisture in the SPOC process allows the condensation of this moisture to occur at temperatures that are beneficial to the steam cycle, e.g., to carry out feedwater heating duties.

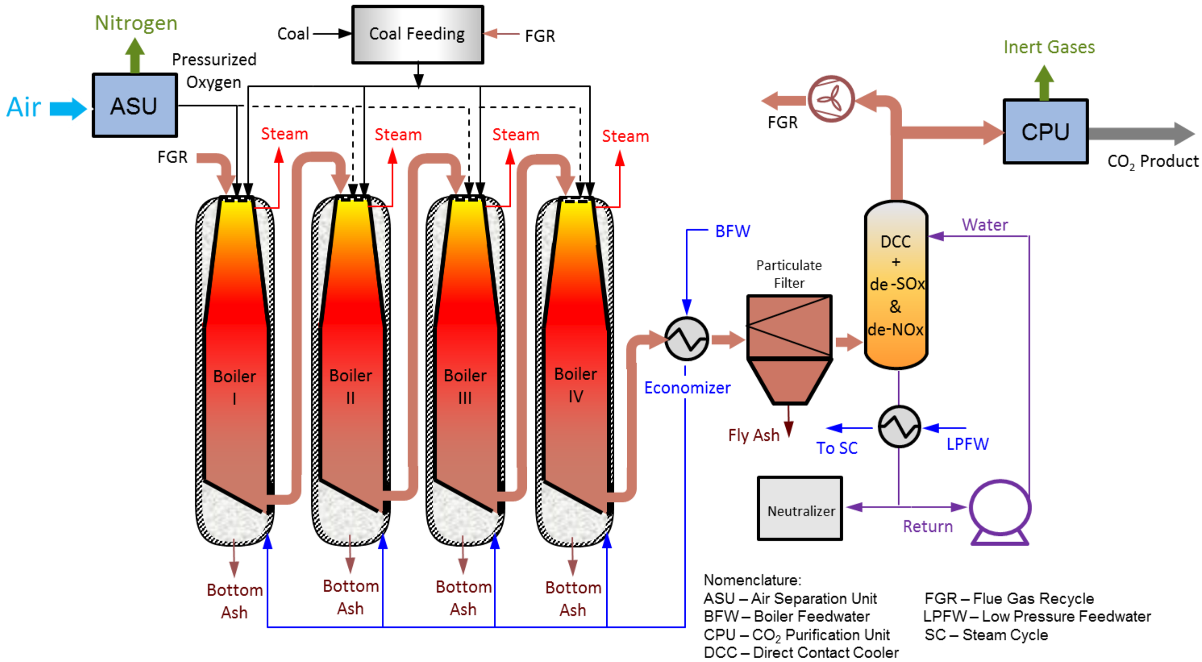

Fig. 1. Staged pressurized oxy-combustion.

The Electric Power Research Institute, Inc. (EPRI), WUSTL, American Air Liquide Inc. (AAL), and Doosan Babcock Limited (DBL) investigated the potential for SPOC with support from the U.S. Department of Energy (DOE) both as an efficient low-carbon electricity generating technology and for enhanced flexibility capability given the system ability to adjust firing systems on a per-stage basis. The SPOC concept was reviewed by DBL, a boiler plant original equipment manufacturer (OEM), to determine what would be required to deliver a feasible working system within acceptable design criteria that would deliver 550 MWe of net output power to allow direct comparison with National Energy Technology Laboratory (NETL) baseline cases [2,3]:

Table 1. NETL baseline cases

Baseline Case	Fuel	CO_2 Capture	Steam Cycle Conditions (Pressure/Temperature)
S12A Air-Fired Supercritical Pulverized Coal (PC)	Powder River Basin (PRB)	0%	241barg/593°C/593°C
S12B Air-Fired Supercritical PC with Post-Combustion Capture	PRB	90%	241barg/593°C/593°C
S12F Oxy-combustion Supercritical PC	PRB	90%	241barg/593°C/593°C

The steam cycle used for the SPOC has identical steam and reheat conditions. The only salient difference between the steam turbine system for these cases and the SPOC steam system is the degree of heat recovery that is possible with SPOC due to sensible and latent heat recovery at the back end of the process.

The combustion system needed at this scale was assessed by WUSTL using computational fluid dynamics (CFD) modeling tools, allowing operating temperatures and heat flux profiles to be evaluated. The resultant thermal absorption data were then used for the boiler design, ensuring that the water / steam tubes are operating within acceptable metal temperatures at every point throughout the combustion zone. Combustion testing is being carried out in the WUSTL 100-kWth test facility where temperature profiles, flame stability, burnout characteristics, and performance at low excess oxygen levels were investigated. Radiative heat flux levels obtained from these tests are used to validate the CFD models to ensure that the predictions at the 550-MWe scale are as accurate as possible.

Nomenclature

AAL	American Air Liquide Inc.
ASU	Air Separation Unit
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DBL	Doosan Babcock Limited
DCC	Direct-Contact Cooler
DOE	United States Department of Energy
EPRI	Electric Power Research Institute, Inc.
FGR	Flue Gas Recycle
GCV	Gross Calorific Value (fuel energy inc. moisture)
kWth	Kilowatt thermal (energy)
MWe	Megawatt electric (power)
MWh	Megawatt-hour (energy)
NCV	Net Calorific Value (fuel energy exc. moisture)
NETL	National Energy Technology Laboratory
OEM	Original Equipment Manufacturer
PC	Pulverized Coal
PRB	Powder River Basin (coal type)
SPOC	Staged Pressurized Oxy-Combustion
WUSTL	Washington University in St. Louis

2. Testing and Model Validation

To demonstrate the SPOC boiler design concepts and validate the models, a 100-kWth pressurized combustion facility was designed and constructed. This facility is designed to accommodate a wide variety of gas inlet conditions (e.g., air-fuel equivalence ratio 1~3, oxygen concentration 21~99%) to identify the optimal operating conditions for SPOC process. This 160 m^2 research facility located in Washington University in St. Louis contains a furnace for studies of pressurized combustion or gasification of coal or other fuels, at a pressure up to 20 bar. The test furnace, shown in Figure 2, is approx. 20 ft long and is comprised of multiple sections with access ports for instrumentation.

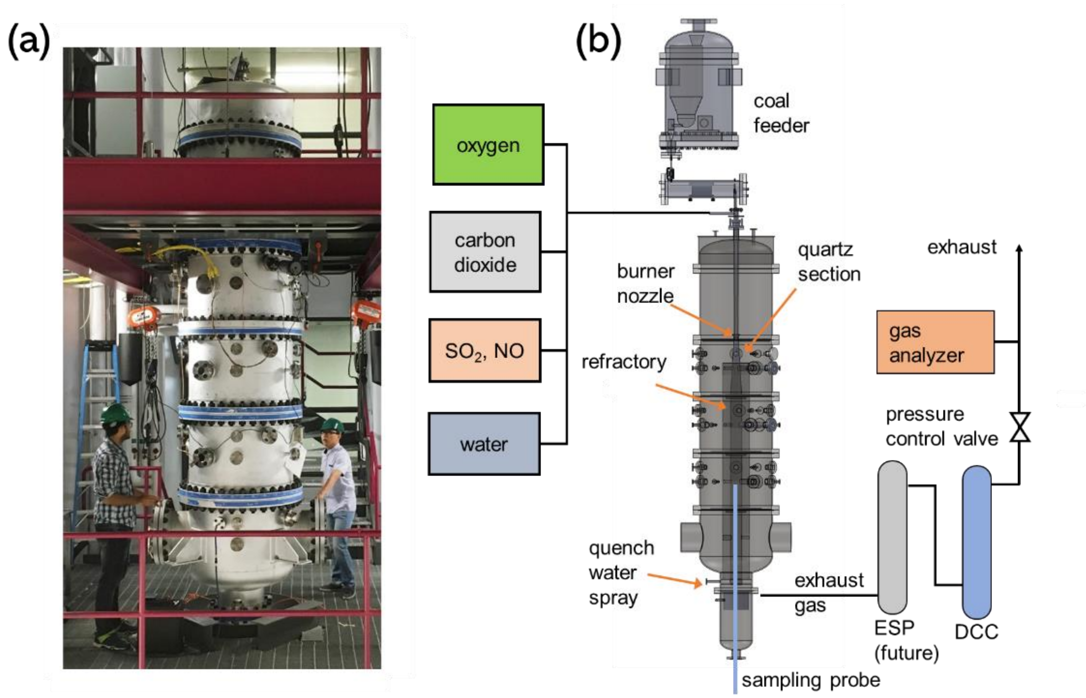

Fig 2. (a) A picture and (b) schematic of the 100-kWth pressurized oxy-combustion facility

This facility includes bulk liquid storage and gas delivery systems for O_2 and CO_2 for pressurized oxy-combustion research. The reactor is made of refractory with an internal diameter of 5.5 inches and it is placed at the center of the pressure vessel, as shown in Figure 3. A conical-shaped quartz tube with ignition and sampling ports was built as the top section of the reactor. It allows for visual access to the flame and for optical diagnostics.

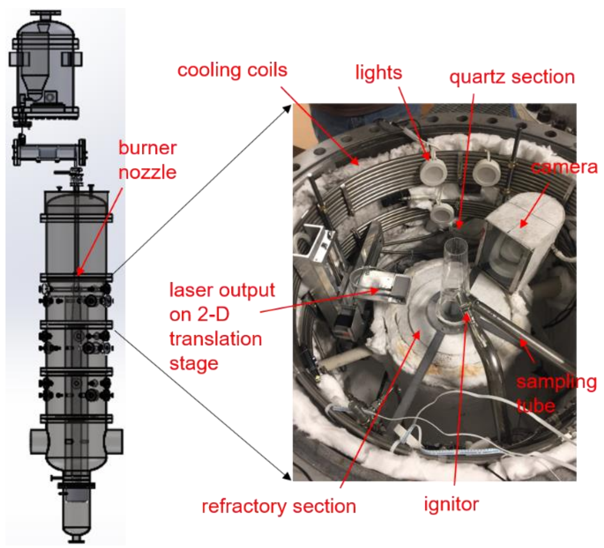

Fig 3. Photograph of SPOC reactor section, featuring quartz section and diagnostics for flame visualization.

Figure 4 shows an example of a down-fired coal flame seen from the quartz tube. Six air-cooled high definition webcams are installed inside the pressurized chamber to observe the flame from multiple angles and provide a complete view of the quartz reactor section, covering the majority of the flame. There are several optical ports on the pressure vessel's side wall, which can be used for high-speed flame videography and heat flux measurement as well. Through high-speed videography detailed information on the flame structure can be readily observed, including the flow field, particle motion, and particle transformation (i.e. particle ignition, volatile release and combustion, and char combustion). Both narrow angle heat flux and ellipsoidal heat flux measurements will be taken using an internally developed line of sight radiometer and a Medtherm Schmidt-Boelter heat flux sensor, respectively. Type K thermocouples are installed along the length of the reactor to remotely monitor the temperature distribution along the reactor wall. A laser diagnostic system, including an RGB three-color laser and fiber optic system is mounted on a multi-axis translation stage which allows for two-dimensional scanning of the flame through the quartz tube, as shown in Figure 3.

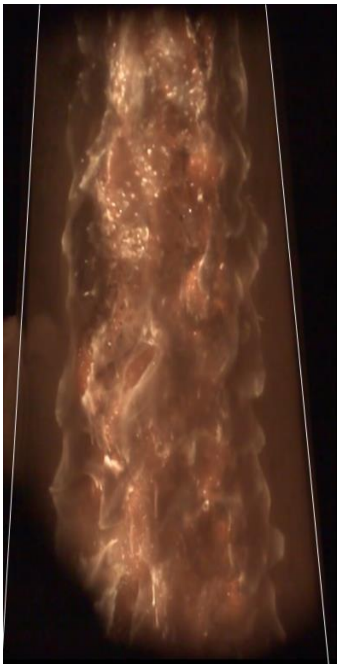

Fig. 4. Downward fired oxy-combustion coal flame.

Two types of pressurized sampling probes are used for sampling particles and gases: a water-cooled sampling probe inserted through the base of the pressure vessel, and a two-stage dilution sampling probe inserted into the reactor through the side ports of the pressure vessel. The two probes can be used to sample gas and particles from different axial and radial locations, providing a full map of gas composition and particle size and composition distribution inside the reactor. A concise summary of the diagnosing capabilities is given in Table 2.

Table 2. Measurement capabilities of the SPOC facility.

Measurement	Device
Wall heat flux (both convective and radiative at port locations)	Medtherm Schmidt-Boelter heat flux sensor
Flue gas composition	Flue gas sampler, HORIBA Multi-gas analyzer
Centerline profiles of gas composition (i.e., CO_2, O_2, CO, H_2O, NOx, SO_2)	Pressurized gas & particle sampler, HORIBA Multi-gas analyzer
Centerline particle size distribution	Pressurized gas & particle sampler, DEKATI Electrical Low-Pressure Impactor (ELPI)
Centerline temperature	Thermocouple
Visual observation of flames	HS camera and HD webcam
Flue gas CO and soot concentration	Flue gas sampler, Horiba Multi-gas analyzer, Optical Particle Sizer (OPS)
Ash carbon concentration	Flue gas sampler, Cyclone, Thermogravimetric Analyzer

An industry-standard Allen Bradley safety and control system with Rockwell Automation software is used for automated operation of the facility. In addition, a Labview-based system is used for high-resolution experimental data acquisition and storage.

A series of preliminary experiment tests have been conducted at 15 bara. First, gaseous combustion was tested at 15 bara with a wide range of operating conditions. The goal of this test was to identify an optimal operating condition for heating the refractory wall during cold start-up. It was found that, even though a down-fired methane flame has a high sooting tendency at elevated pressure, by choosing an optimal operating condition, soot emission can be eliminated. A 40 kWth methane flame with oxidizer-fuel equivalence ratio of 2.2 and 30% v/v overall oxygen fractions in oxidizer streams is identified as the best operating condition for heating up the system. Then transitions from air-fired mode to oxy-fired mode and from methane flame to coal flame were tested at 15 bara and smooth transitions were achieved. Then, target operating conditions at full load (100 kWth, Figure 5) and half load (50 kWth) were tested. It was found that stable coal flame can be achieved without any methane support. Also, no soot and CO emission were detected at the exit of the reactor even when the oxygen fraction at the outlet is as low as 3% v/v. Particle samples at the exit of the reactor also indicate no unburnt carbon content. Flue gas was quenched using a direct contact water spray. This led to low NOx and SOx emissions due to absorption in the cooling water. NOx emissions were also limited due to the absence of nitrogen and the thermal NOx formation mechanism. At the end of the test campaign the total thermal input was pushed to 125 kWth (100 kWth coal and 25 kWth methane) without any operational problems.

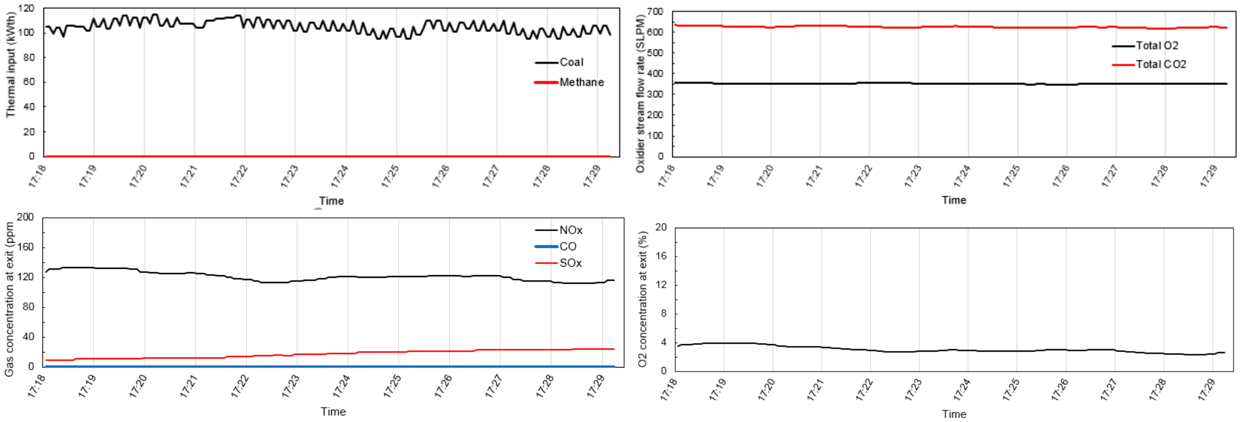

Fig. 5. POC test facility operating data at design operating conditions: 15 bara, 100 kWth.

3. Steam Generator Design

WUSTL had carried out previous work on the steam generator for the SPOC process that envisioned a single vessel design with high-temperature radiant tube surfaces, similar to that found in gasification systems. Each stage had a single downshot combustion module that used concentric tubes located near the bottom for flue gas cooling prior to the subsequent stage. This heating surface arrangement was assessed by DBL and a risk matrix was developed to quantify the probability and consequence of each identified risk and to identify any technical showstoppers. The highest risk items identified were:

- Complexity of design for heating surfaces, headers, and supports. Concentric heating surface contained within each SPOC pressure vessel presents several significant mechanical design challenges.
- Potential for excessive ash slagging and fouling resulting in impaired process performance and availability. Concentric heating surface design is not conducive to typical online cleaning methods

The concept design was adjusted to address the key risk items identified during the risk assessment exercise, which resulted in a two vessel per stage approach (Figure 6). The first vessel is a combustion module that is comprised of a completely open pass with evaporative membrane tube walls installed at the perimeter. Although the combustion process used in SPOC has low lateral mixing requirements (no swirl is used in this design), the shape of the inside of the combustion module was carefully configured to deliver an acceptable balance between design and manufacturing complexity and the gas flow characteristics during the combustion process. The combustion module is designed to be tall enough to ensure that the flue gas is cooled sufficiently below the ash initial deformation temperature prior to allowing the gas to change direction and be passed to the next vessel. This ensures that the ash generated in the combustion forms solid particles before exiting, ensuring that downstream systems are not exposed to sticky ash particles that can attach to internal surfaces and form large, performance impacting deposits.

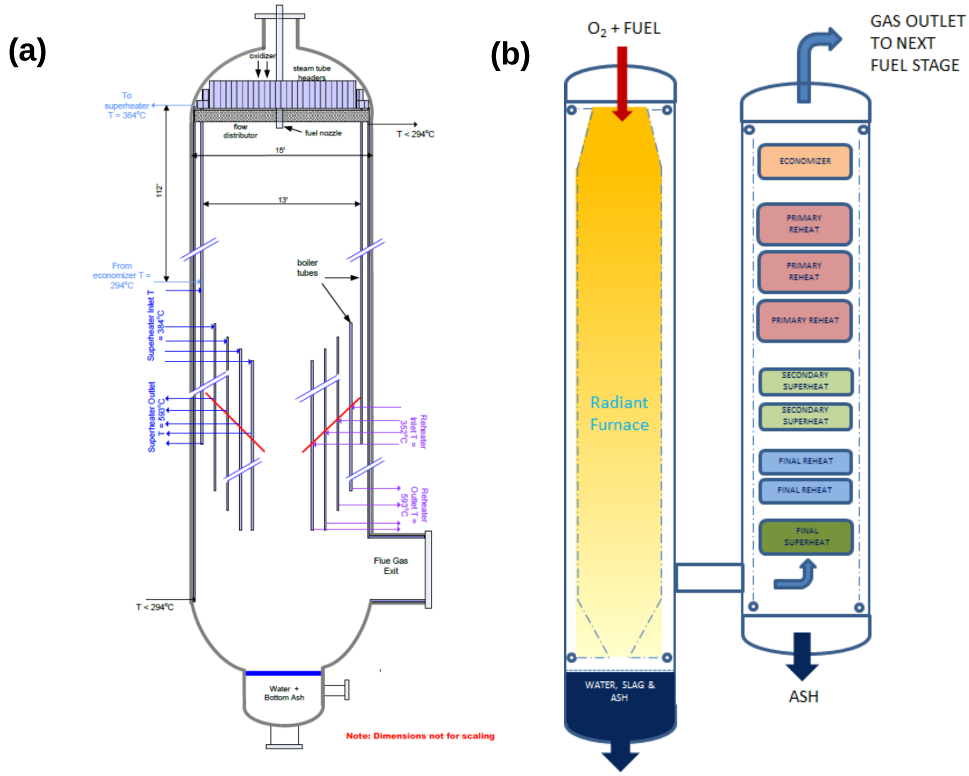

Fig. 6. (a) Original configuration and (b) new two-pass concept for a single SPOC stage.

This revised concept design addressed the key risk items identified in the initial OEM review, although it was noted that there remains a degree of uncertainty due to the small scale of performance testing, a lack of boiler surface during these tests, and the reliance on CFD modeling for performance assessment.

3.1. Combustion Module

One important criterion for all components in this design concept is the ability to manufacture the equipment in a factory environment and be able to transport completed modules to the site using conventional road infrastructure, allowing for minimal construction at the site location. This philosophy is critical in achieving the lowest possible capital costs as site-based construction would significantly increase the cost. The pressure vessels were therefore limited to an outside diameter of 4.2 m. DBL determined that the inner combustor membrane tube perimeter would need to be restricted to 3.86 m to allow for the pressure vessel thickness and a cavity annulus to accommodate piping connections and cooling gas to ensure the pressure vessel is not substantially heated. Using this sizing limitation, WUSTL assessed the heat flux generated in the combustion module using CFD modeling for a four-stage, 550-MWe scale SPOC unit.

The original design concept involved having a conical section extending almost 50% of the combustor module height. This arrangement would require complex boiler tube configurations and deliver uneven tube heating that would lead to temperature differences between tube elements feeding common riser headers at the top of the module. Additionally, the mechanical support for this arrangement would be complex as unheated sling tubes would be necessary to support the lower sections, as the internal structure needs to be top supported to facilitate sufficient thermal expansion allowance. Finally, the quantity of surface available to absorb heat at the top sections of the furnace was reduced in comparison to the lower sections, exposing previously heated steam to high heat fluxes.

To counter these issues, the arrangement was revised, and Figure 7, which shows the resulting heat flux profile as compared to the original design. The heat flux for the revised design is flatter and more manageable. The combustion module considered a maximum heat flux of 450 kW/m^2 using 13CrMo44/ ASME SA213 T12 tubing material.

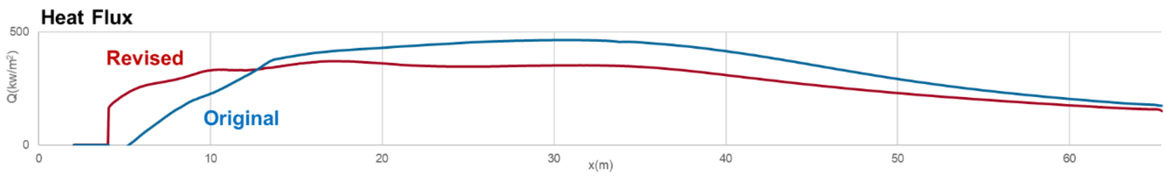

Fig. 7. Original heat flux profiles and those from the revised combustion module envelope.

3.2. Convective Module

The convective module has been configured to be an up-flow arrangement with a square cross section heat exchanger cavity bounded by membrane wall tubes. This arrangement allows banks of tubes to be installed with conventional geometries, ensuring each steam-side flow path is as even as possible, minimizing the risk of flow imbalance between tube elements. The square membrane enclosure surface also facilitates sufficient space between the circular pressure vessel and the membrane walls. This in turn accommodates pressure-part components such as stub headers, minimizing the need for extensive pressure vessel penetrations and hence reducing cost.

The banks were sized using proprietary boiler performance modelling software, updated to allow design calculations to be conducted at the elevated pressure required for SPOC operation. This software has been extensively validated against the performance of real plants for a wide range of operating conditions and a broad set of fuels. All of this was, however, conducted at near atmospheric conditions, given the requirements of air firing and atmospheric oxy-combustion. To ensure the flue gas properties predictions at elevated pressures were accurate, the software was tested against the property predictions for density, viscosity, heat capacity, and thermal conductivity from commercial software packages (Thermoflex, Aspen HYSYS®, and ANSYS® FLUENT) to verify the properties. Using the maximum observed differences, the heat transfer calculations were determined to have a maximum relative error of less than 4% and the OEM boiler design tool modifications were therefore deemed sufficiently accurate.

Additionally, the radiative and convective heat transfer predictions for the boiler performance model were compared against CFD predictions for the same bank geometry, gas mass flux, gas composition, and tube outer wall surface temperature. This exercise showed that the OEM design tool delivered a more conservative design (i.e., lower overall heat transfer coefficients) and hence was used for the bank performance predictions and subsequent sizing to yield a larger exchanger size.

The optimized arrangement was developed to be in series on the gas side using hot FGR from the exit of Stage 4 to ensure that the Stage 1 design is identical to the subsequent stages. Consequently, the steam/water circuit is split equally across all the stages (i.e., identical superheater, reheater, and economizer tube banks). It should be noted that hot FGR can be a challenging scenario, given that the flue gas will contain a substantial fly ash component, making the mechanical design of the blower necessary to withstand erosion, or to have a high-temperature particulate removal device for the FGR stream. A lower risk option is to recycle flue gas from after the main particulate removal and direct-contact cooler (DCC) modules. This however will complicate the performance characteristics of the first stage relative to the others.

The design exercise determined that two pressure vessels are needed for a single SPOC stage with four total SPOC stages required for the 550-MWe SPOC power plant as shown in Figure 8. The combustion gases along with any particulate matter pass in downflow configuration in the combustion module, where there is a direction change at the bottom to aid ash drop-out.

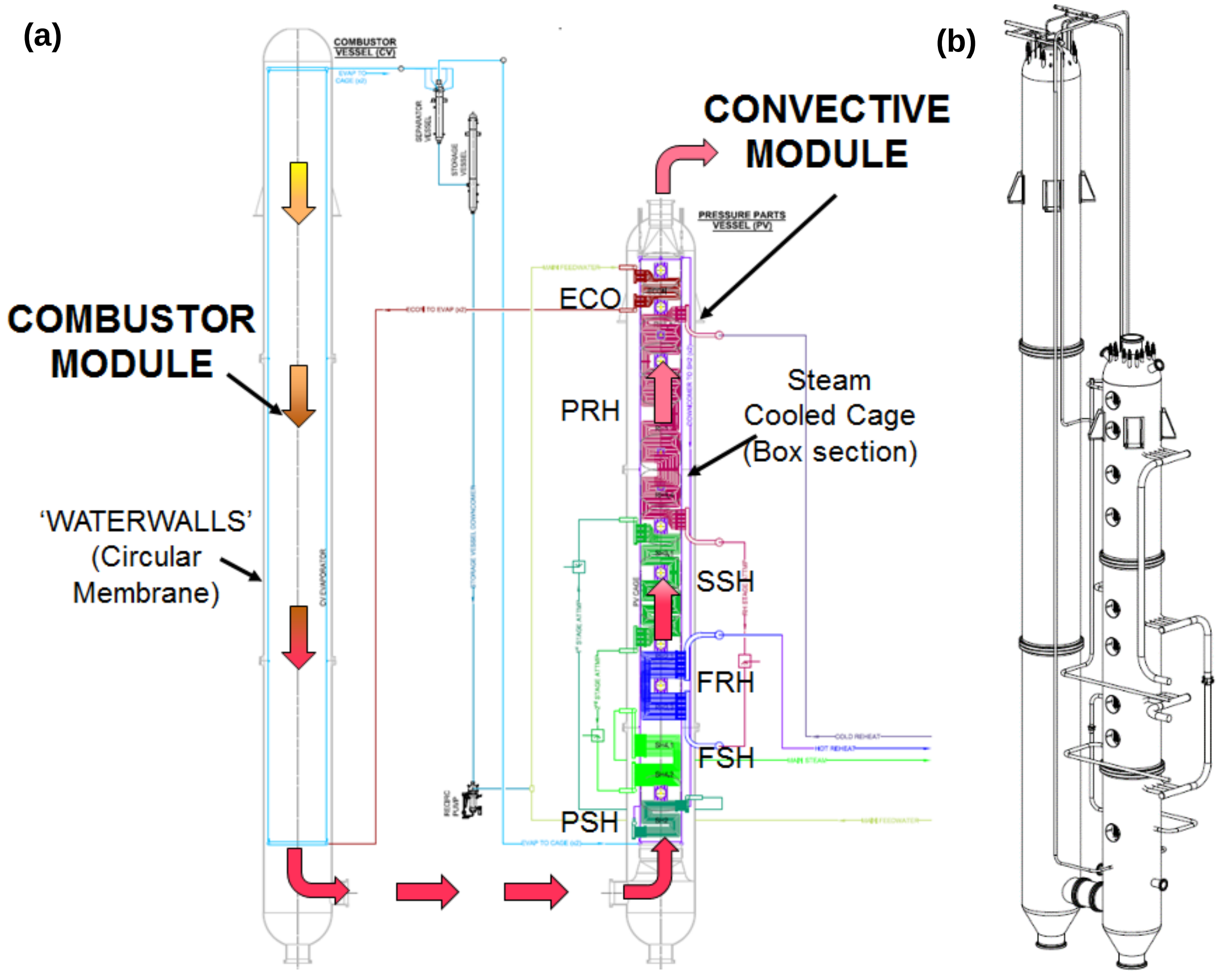

Fig. 8. (a) Internal components of a SPOC stage and (b) Isometric schematic of a SPOC stage showing external steam piping.

4. System Integration

The steam turbine used for the NETL atmospheric oxy-combustion Case 12F does exhibit some low-temperature heat recovery from the air separation unit (ASU) and the downstream CO_2 compression intercoolers. The SPOC process offers far greater low-temperature thermal recovery opportunities due to the latent heat of moisture in the flue gases produced that has a suitably higher condensation temperature due to the elevated pressure. The exit temperature of the convection modules was defined at 340°C to reflect conventional economiser exit conditions. Because of the FGR being carried out in a hot basis, there is no gas-gas heater in this configuration and so the sensible heat from this flue gas can be captured for use in the steam cycle where appropriate.

4.1. Heat Recovery

A pre-economizer bank installed prior to the dust removal module was configured to capture this energy into the steam cycle. The deaerator outlet temperature of the steam cycle is available at a temperature that can cool the flue gases towards a targeted 200°C, after which the moisture dew point will be reached in this system. Following dust removal, the flue gas is cooled in a DCC that also removes a significant amount of sulfur and nitrogen oxides due to the elevated pressure conditions. The latent heat absorbed in the DCC is recovered in the DCC cooler heat exchanger. The overall heat recovery system for the 550-MWe SPOC plant along with a graph of the temperature change vs. the heat duty through the system is shown in Figure 9.

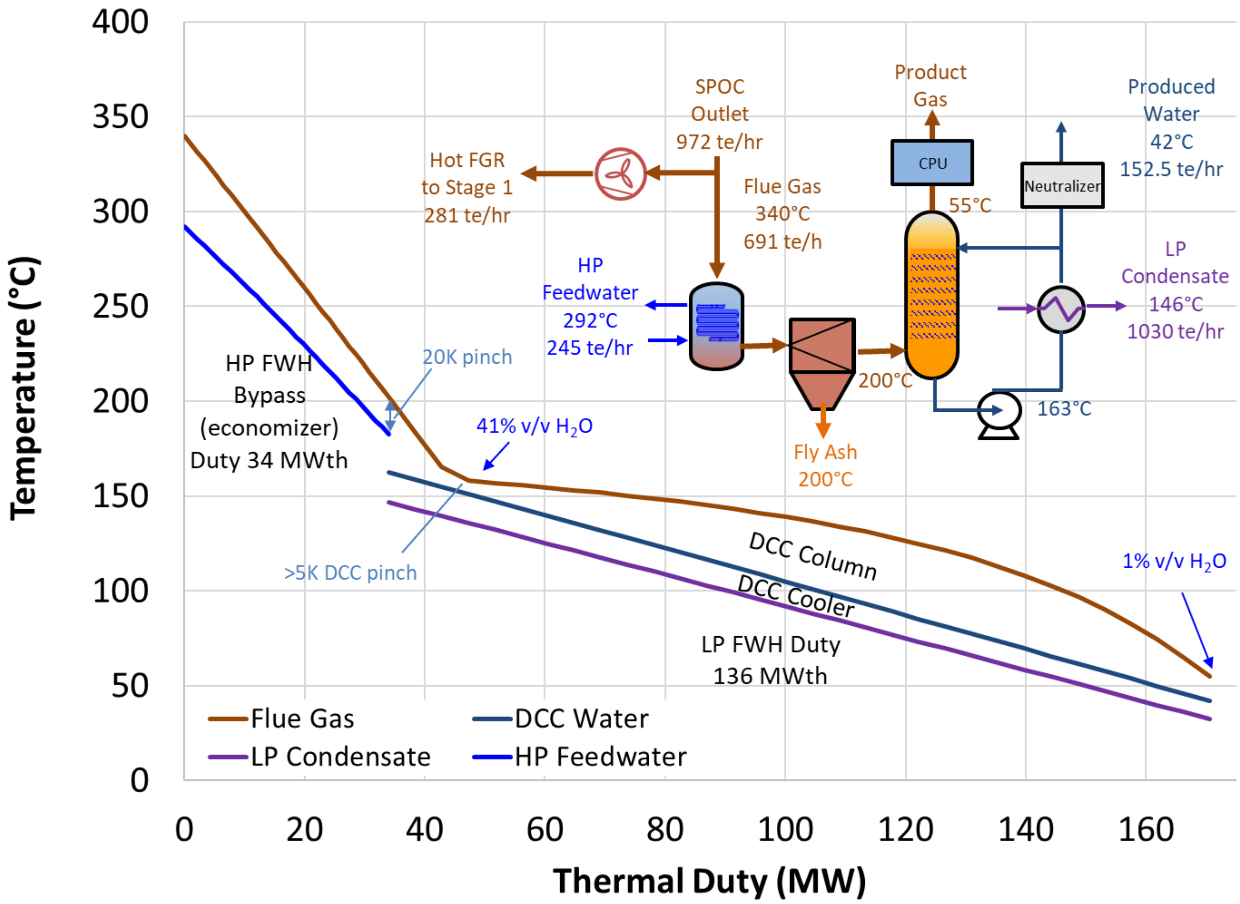

Fig. 9. Heat recovery temperature-heat plot for a 550-MWe scale SPOC plant.

The energy recovered from the flue gas can be added to the heat recovery from the ASU and the compression plant to allow 100% bypassing of the low-pressure feedwater heaters and partial bypassing of the high-pressure feedwater heaters. In a dedicated SPOC design, there would not be any requirement for low-pressure feedwater heaters, reducing capital costs. The increased heat recovery delivers a 6% reduction in main steam flow for the same gross power output.

4.2. Flexibility Options

SPOC offers unique opportunities to deliver a high degree of turndown due to the potential ability to bypass stages, thereby delivering reduced output while the remaining operational stages are firing at full load. Additionally, the firing rate of all stages can be reduced, delivering an even steam generation between all stages. Testing at WUSTL has successfully demonstrated 50% turndown with successful burnout achieved at the targeted excess oxygen level of 3% oxygen at the stage outlet. Hence, a combination of burner turndown and stage bypassing could potentially facilitate 100% load down to below 12% on a four-stage SPOC system.

5. Conclusions

The SPOC process being developed by WUSTL has the potential to offer highly flexible and efficient low-carbon coal-fuelled power generation. The revised boiler design proposed minimizes the risk of tube overheating due to excessive heat flux, ash management concerns, and water- and steam-side flow stability. A 550-MWe system can be configured with four ground-transportable modular stages, reducing field erection costs and maximizing factory quality control throughout the construction process. The SPOC arrangement potentially offers significant turndown opportunities, since a combination of burner turndown and stage bypassing could be employed.

Acknowledgements

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