FINAL EXECUTIVE SUMMARY REPORT

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Project Title: Evaluation of Staged Oxyfuel Combustion for CO_2 Capture

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BACKGROUND

This report contains a summary of work undertaken to develop an advanced oxy-combustion technology, which aims to drastically reduce the costs associated with capture of carbon dioxide from new coal-fired power plants. Coal-based electric power generation represents one of the largest single contributors of global CO_2 emissions. Carbon capture and sequestration (CCS) is viewed by the IEA and many other organizations as a crucial piece within the set of available tools to combat the rise in global temperature, along with wide-scale deployment of renewable and nuclear power, and improvements in efficiencies. Furthermore, the construction of new coal-fired power plants without CCS is currently prohibited by EPA regulations, as part of the President's Clean Power Plan. Meanwhile, CCS is not required for new power plants powered by natural gas. The currently low price of natural gas and the uneven EPA carbon regulations have led to a stoppage of planning for new coal-fired generation and the retirement of many coal-fired assets in the U.S., and has also led to reductions in research and development efforts. While current policies encourage "fuel switching", the insurgence of natural gas should only be considered as a "bridge" solution to climate change since the goal of holding global temperature to 2 degrees Celsius, as set forth in the recent COP 21 meeting in Paris, cannot be achieved simply by replacing coal with gas. Therefore, contrary to current trends, large investments in CCS technologies for coal-fired generation are needed to achieve reliable, safe, affordable, and carbon-neutral baseload power in the next 50 years.

The three main ways to achieve CO_2 capture from coal-based power generation sources include: 1) pre-combustion capture, wherein the carbon from the fuel is separated (as CO_2)

before combustion using chemical processes, e.g., the Integrated Gasification Combined Cycle (IGCC) system, 2) post-combustion capture, wherein after normal combustion the carbon dioxide in the flue gas is separated by physico-chemical processes, and 3) oxy-coal combustion, where coal is combusted with nearly-pure oxygen and recycled flue gas to obtain a high purity stream of CO_2.

A first generation oxy-combustion power plant would utilize a large volume of recycled flue gas and operate at near atmospheric pressure. The recycled flue gas is used to control flame temperature and heat transfer in the boiler to yield conditions similar to those of traditional air-fired boilers, and, under the right circumstances, an existing boiler may be retrofit for oxy-combustion using this approach. A comparison of different carbon capture methods in terms of cost favors oxy-combustion for new plants, yet the costs are still prohibitively high. This project seeks to develop an advanced oxy-combustion approach that is specifically aimed at new plants (not retrofits), which incorporates combustion at elevated pressure and better utilizes the oxygen, which results in significant improvements in efficiency and reduced costs.

The requirement of high pressure CO_2 for geologic storage or enhanced oil recovery allows for pressurization of the oxy-combustion process without an added cost, and pressurized oxy-combustion has many benefits, including: 1) the moisture in the flue gas condenses at higher temperature, and thus the latent heat of condensation can be utilized to improve the overall cycle efficiency. 2) Since the latent heat is recovered, the penalty associated with using high-moisture fuels is reduced, thereby making PRB coal more valuable in this application. 3) the gas volume is greatly reduced; therefore, the size and cost of equipment can be reduced, 4) SOx and NOx can be more easily removed, and at less cost, at elevated pressure by converting them to weak acids in a water wash column, 5) at higher pressure, the convective heat transfer to boiler tubes is increased for a given mean velocity, and 6) air ingress, which normally occurs in induced-draft systems, is avoided, thereby increasing the CO_2 concentration of the combustion products and reducing purification costs. The elimination of air ingress has the potential to remove the need for cryogenic distillation within the CO_2 purification process, and result in a significant cost savings.

In this work, a unique pressurized oxy-combustion process was developed that aims to further improve the efficiency and costs by reducing the recycling of flue gas. Normally, in the absence of recycled flue gas or another inert gas, combustion of fuel in an atmosphere of high oxygen concentration would result in a dramatic increase in temperature of the combustion products and the rate of radiant heat transfer. The resulting high heat flux to the boiler tubes may, in this case, result in tube surface temperatures that exceed safe operating limits. In the Staged Pressurized Oxy-Combustion (SPOC) process (Figure 1), this problem is addressed by staging the delivery of fuel, carefully controlling flame shape, and utilizing the favorable radiation heat transfer characteristics that occur in pressurized combustion of pulverized coal.

PROJECT GOALS

The main objectives of this project were to investigate the potential for the proposed SPOC concept through modeling and combustion experiments at 1 atm, and to utilize the knowledge gained to design a burner and boiler to enable the SPOC approach. An ancillary goal was to perform a techno-economic study of a theoretical 550 MWe power plant that incorporates this technology while using sub-bituminous coal from the Powder River Basin. Support for the techno-economic study was largely provided by US DOE (FE#0009702), and PRB coal was added to the fuels

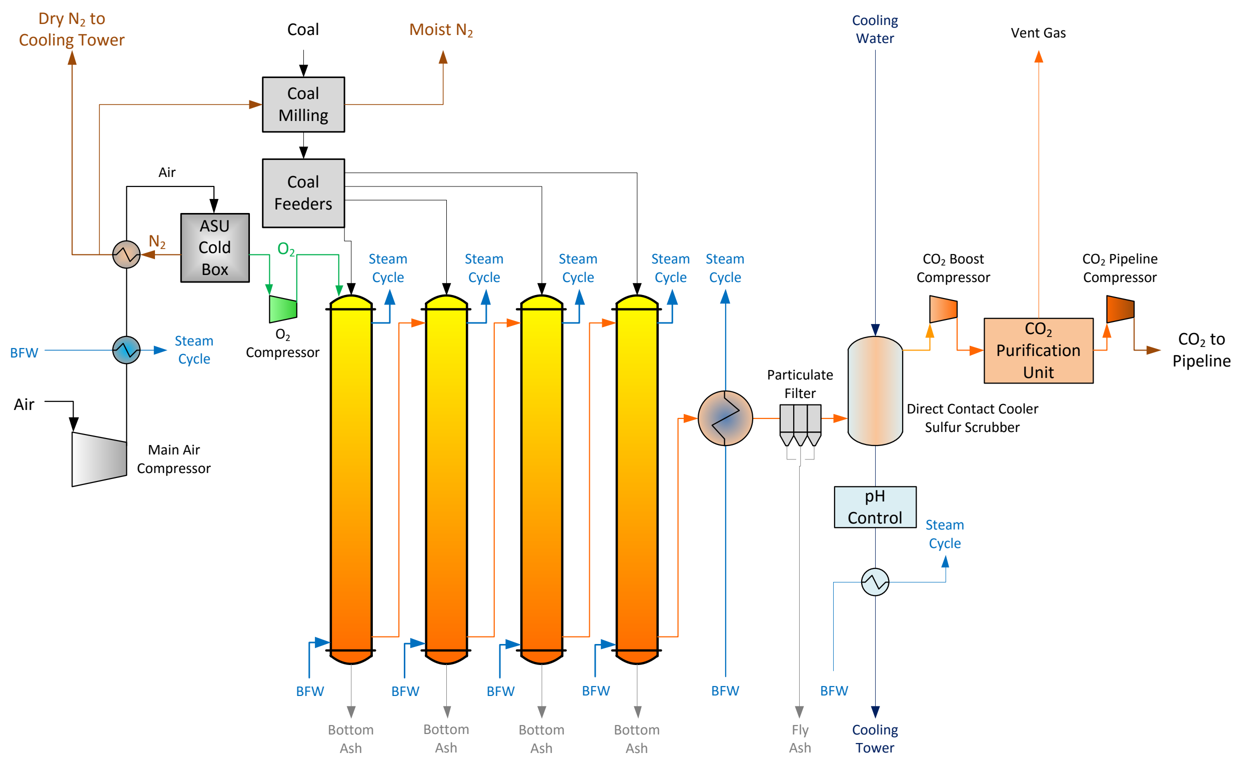

Figure 1. – Staged, Pressurized Oxy-Combustion: Process Flow Diagram

considered in the study since PRB is particularly well-suited for this application due to its low cost and low sulfur content.

It was proposed to investigate the use of coal-water slurry as the fuel, since a slurry may be readily pumped to elevated pressure and sprayed into the combustion chamber. One objective of this work, in collaboration with West Virginia University, was to develop a method to produce a stable coal-water slurry using PRB coal, and to utilize this fuel in subsequent combustion tests.

Combustion tests were planned and conducted utilizing two systems: a 30 kWt lab-scale furnace and a 1 MWt small pilot furnace at the Advanced Coal & Energy Research Facility at Washington University. This first stage of experiments was conducted at atmospheric pressure and was accompanied by computational fluid dynamics modelling. The purpose of these experiments was to study the effects of fuel staging, in the absence of flue gas recycle, on important combustion characteristics such as temperature, radiant heat transfer, ash properties, and pollutant formation.

RESULTS

A power plant incorporating the Staged, Pressurized Oxy-Combustion (SPOC) process with 90% carbon capture was modelled using the APSEN PLUS systems software. In the model, the carbon dioxide was purified to meet standards for enhanced oil recovery. Results, shown in Figure 2, revealed a net plant efficiency (HHV) of 35.7% when using subbituminous PRB coal, which outperforms the current national average of the US coal fleet (approx 32.5% HHV). The penalty in plant efficiency due to the addition of carbon capture is reduced by more than half - from 10 percentage points in the atmospheric pressure oxy-combustion plant (as reported by DOE/NETL) to about 4 percentage points due to the SPOC process. The associated increase in cost of electricity (COE) associated with this process is very near the DOE target of 35%.

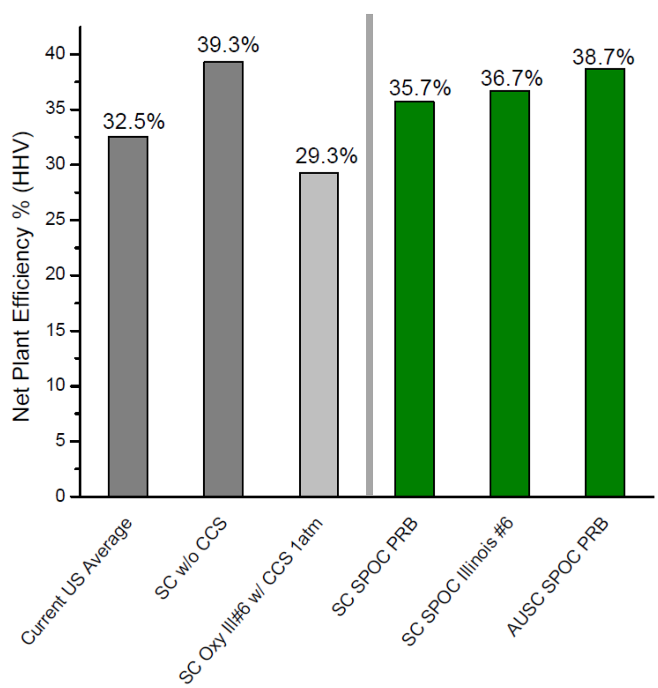

Figure 2. – SPOC plant efficiency (green), compared to reference cases (grey). SC = supercritical steam (3500 psig/1100 °F), AUSC = advanced ultra-supercritical (4000 psig/1400 °F)

Parametric analyses on the effects of combustor operating pressure and fuel moisture were also performed. It was found that combustor pressure has only a minor impact beyond 15 bar, therefore, this is considered to be the optimal pressure. The effect of fuel moisture was found to be quite significant. Net plant efficiency gradually decreases with increasing fuel moisture until the heat saturation value, beyond which additional latent heat cannot be integrated into the steam cycle and the efficiency reduction is more drastic. For this reason, dry feeding of pulverized coal is preferred over coal-water slurry fuel.

Coal water slurry (CWS) of PRB coal was prepared and its static stability and rheology were characterized. The loading of coal ranged from 30 wt% to 50 wt%. Both ionic and nonionic surfactants were tested as additives in experiments. Triton X-100 was found to be a good surfactant with respect to static stability, as the sediment with Triton X-100 is much less. Adding Triton X-100 reduces the viscosity of the CWS with coal loadings of 30 wt% and 40 wt%. Though the viscosities for coal loadings of 42.5 wt% and 45 wt% were higher when Triton X-100 was added, the static stability was significantly better than the samples without surfactant. The highest coal loading achieved for PRB slurry with reasonable viscosity was 42.5 wt%. Preliminary combustion tests of the as-produced CWS were conducted, however, the fuel injection was unreliable due to clogging in the nozzle. In light of the process modeling results, which showed that plant efficiency is significantly reduced when using CWS fuel, further combustion tests of CWS were abandoned in favor of a focused effort using surface-dried fuel.

In Year 1, an experimental test campaign was undertaken at the Advanced Coal & Energy Research Facility, which houses a 1 MWt oxy-combustion test furnace with a swirl-stabilized burner (Figure 3). The aim of the testing was to characterize the oxy-combustion of coal under conditions of decreased flue gas recirculation or, similarly, increased oxygen concentration, in order to simulate conditions in the early stages of the staged combustion process. In these early stages, there is a large excess of O_2 that acts as a dilution gas to reduce the temperature of combustion products. Combustion tests were conducted utilizing oxygen-enriched air, up to 50%v O_2. Measurements of wall radiative heat flux were obtained. Gas temperature measurements were carried out using a suction pyrometer, and gaseous concentration profile (O_2, CO_2, CO, NOx) were obtained. These measurements were compared against predictions from the CFD combustion model (Figure 4), and reasonably good agreement was obtained.

Figure 3. – 1 MWt Oxy-combustion furnace at the Advanced Coal & Energy Research Facility (ACERF)

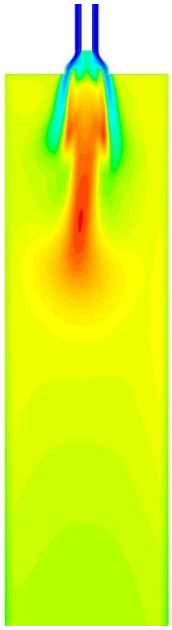

Figure 4. – False-color temperature distribution during pulverized coal combustion, as predicted by CFD modeling

An oxygen concentration of 50% in the secondary oxidant resulted in an increase in peak radiative heat flux of 37%, when compared to air-firing. In spite of the increased local flame temperature in the combustion zone, it was found that the post-flame temperature remained largely unaffected by the oxygen enrichment, which was predicted. At 50% O_2, however, the resulting flame was very short, which limited our ability to accurately measure temperature and heat flux profiles. More importantly, CFD modeling suggested that a long flame was necessary in order to achieve a distributed heat release while maintaining optimal radiant heat flux levels under conditions of high oxygen concentration. To achieve the desired flame shape, a new burner and chamber design was required.

The team, guided by CFD simulation, designed and constructed a new 1 atm, 30 kWt test furnace and burner (Figure 5). This furnace was specifically designed for high-temperature combustion of coal in pure oxygen. The burner was designed to operate with axial flow (no swirl), resulting in a stable jet flame. This no-swirl design also acted to reduce ash deposition and slagging on the furnace walls. This unique down-fired furnace was made long and narrow to mimic the high aspect ratio typical of pressure vessels and to achieve a sufficiently high gas velocity such that the effects of buoyancy were minimal.

Stable and safe combustion of both pulverized coal and gaseous fuels was demonstrated in atmospheres of 100% O_2. Despite the fact that combustion in pure O_2 resulted in local regions of very high combustion temperature, the furnace and burner design proved successful in preventing flame impingement on the wall and wall overheating. Furthermore, no measureable ash deposition on the furnace walls was detected while operating over a period of several hours. The knowledge gained from the design and operation of this facility has been implemented in the construction of a new pressurized oxy-combustion test furnace which will be operating in 2016. Meanwhile, this 30 kWt facility will continue to be a valuable asset for the study of particle formation and deposition under conditions of very high flame temperature.

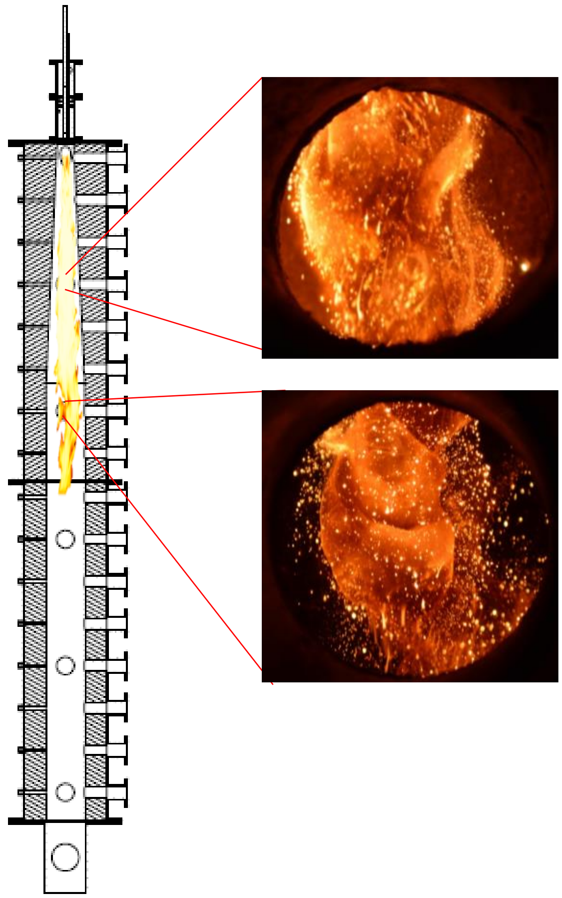

Figure 5. – Schematic of 30 kWt test furnace. Images obtained from high-speed camera show combustion of pulverized coal (with CO_2 carrier gas) in atmosphere of 100% oxygen.

CONCLUSION

The funding allocated by the Wyoming Legislature and administered by the Advanced Conversion Task Force and the University of Wyoming, and the matching funds allocated by the Consortium for Clean Coal Utilization, with support from Peabody Energy, Arch Coal and Ameren, provided crucial early-stage seed funding to develop the Staged, Pressurized Oxy-Combustion concept, which holds promise as a low-cost approach to carbon capture from coal-fired power plants. The work conducted under this program has been disseminated in 5 peer-reviewed journals and numerous technical conferences, and can be found in two PhD dissertations. The successful prototype design, construction and testing conducted under this project has led to further investment by the U.S. DOE (FE#0009702, Phase II) to construct the aforementioned 100 kWt facility for pressurized oxy-combustion, which has a pressure capacity of 15 bar. In addition, Washington University has joined the University of Wyoming as a member of the U.S.-China Clean Energy Research Center (CERC) – Advanced Coal Technology Consortium. Over the next five years, numerous research activities are planned which aim to further develop the SPOC technology. These activities include extensive testing and research in the 100 kWt facility to demonstrate stable and controlled combustion under conditions of elevated pressure and oxygen concentration, obtain experimental data for model improvement and optimize the design. Other plans include dynamic plant modeling and detailed combustion modeling in preparation for a potential 10 MWe pilot scale demonstration plant. Industrial partners are currently being sought to develop a pilot project.