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Thermodynamic analysis of a directly heated oxyfuel supercritical power system

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HIGHLIGHTS

- A thermodynamic analysis of a supercritical power cycle is presented.
- The supercritical power cycle is modeled using ASPEN HYSYS®.
- A liquid methane and oxygen feed system is more efficient than a gaseous system.
- CO_2 recirculated in gas form is 10.6% more efficient than when in liquid form.
- Commercially available technologies permit liquid feed system delivery.

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ABSTRACT

Directly heated supercritical oxy-fuel gas turbines have potential to provide a higher thermal efficiency and lower pollutant emissions compared to current gas turbine systems. Motivated by the advantages of an oxyfuel-based directly heated supercritical power system, this paper presents an analysis of different operating conditions using ASPEN HYSYS®. This study first investigates the efficiency of gaseous or liquid methane and oxygen feed systems. *T-s* and *P-v* diagrams are generated and compared to each other to determine which is more efficient. The analysis revealed that the entropy generated during the combustion process for a liquid feed system is approximately three times higher than when methane and oxygen are compressed in gaseous form and delivered to the combustor and burned. To mitigate the high temperatures (3300 K) of the methane and oxygen combustion reaction, carbon dioxide is recirculated. For this portion of the system, the use of gaseous and liquid carbon dioxide recirculation loops and their corresponding efficiencies are determined. The investigation shows that the system yielded a higher net efficiency of 55.1% when gaseous carbon dioxide is recirculated as a diluent with liquid methane and oxygen delivery to the combustor.

1. Introduction and background

Oxy-fuel combustion involves burning a hydrocarbon with oxygen resulting in an exhaust stream which is composed mainly of carbon dioxide and water vapor [1–3]. The advantages of this system are that higher temperatures theoretically allow for higher attainable efficiencies, the exhaust products are free of NO_x, products can be processed and steam condensed, thereby allowing for capture of as high as 100% carbon dioxide at the post-combustion stage [2–6]. Since carbon dioxide produced in the exhaust stream is high purity, minimal processing is required, allowing for less energy intensive carbon capture. Furthermore, oxycombustion could be applied to existing technologies while maintaining similar or higher efficiencies compared to air fired systems despite additional parasitic loads of the air separation and carbon capture units [7].

Buhre et al. [3] explain that in some cases superior performance over an air fired system can be achieved if oxy-fuel combustion is employed in a coal-fired power generation system. The exhaust of such systems mostly consists of carbon dioxide and water vapor, which contain different thermal properties compared to air based systems containing nitrogen. Some studies have shown that the constituents of an oxy-based system can increase the heat transfer in the convective unit of the boiler resulting in higher efficiencies. A study by Stadler et al. [4] showed that a net efficiency of 41% is achieved for an oxy-coal fired plant after considering the power required for the air separation and carbon capture units. Other studies show that the performance of an oxy-coal based power plant depend upon the pressure of the combustion chamber [5].

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Nomenclature

English	
P	pressure (kPa)
P_r	reduced Pressure (kPa)
P_{cr}	critical pressure (kPa)
T	temperature (K)
T_r	reduced temperature (K)
T_{cr}	critical temperature (K)
C_p	specific heat at constant pressure (J/mol K)
LHV	lower heating value (kJ/kg)
R	gas constant (J/mol K)
z	compressibility factor (–)
S	entropy (kJ/kg)
Greek	
γ	specific heat ratio (–)
η_{poly}	polytropic efficiency (–)
η_{net}	net efficiency (–)
η_{thermal}	thermal efficiency (–)

Hong et al. [5] describes that a pressurized oxy-coal combustion system demonstrates higher thermal energy recovery and gross power output compared to an atmospheric oxy-combustion system. The study revealed that efficiency increases by 2% when the combustion pressure increases from 0.1 to 1 MPa. However, operation of oxy-systems at elevated pressures and temperatures is not feasible in many cases since existing materials limit the maximum operating conditions. To fall within current material operability ranges one must either reduce the pressure or temperature during combustion. Previous studies have investigated the effects of flame temperature reduction for an oxy-combustion system. These studies have found that in order to reach an equivalent air-fired adiabatic flame temperature, two thirds by volume of flue gas or diluents is necessary to be recirculated [1,3,8–10]. Hu and Yan [8] evaluate the effect of recycled flue gas on oxy-coal combustion. The authors observed that the flue gas recycle rate decreases with the increment of oxidant (O_2) added. Kunze and Spliethoff [11] analyze the improvement of efficiency in an Integrated Gasification Combined Cycle (IGCC) system when an oxy-fuel combustion system is implemented. The analysis shows an improvement of efficiency of 7% when using oxy-fuel combustion instead of conventional air-based combustion processes. In this same study the authors also mention the major modifications needed for such a system including the necessary abundance of steam.

Gopan et al. [12] studied the use of a novel Staged, Pressurized Oxy-Combustion (SPOC) process using ASPEN Plus. In their model, this process is shown to reduce auxiliary loads associated with flue gas recycle and cleanup. An improvement in efficiency of over 6% points was achieved compared to current oxy-combustion technology. Rajhi et al. [13] developed different gas radiation models for air and oxy-combustion with CO_2 diluents. Based on their findings the exponential wide banned model matched closely with experimental data for boiler applications. Another study performed a thermodynamic analysis of a supercritical power plant fed by coal [14]. The steam power plant analyzed had a power rating of 600 MW operating at 650 °C and 30 MPa and used a circulating fluidized bed boiler working on oxy-combustion technology. This study resulted in a net efficiency prediction of 40% for a fuel with a moisture content of 10%. Bhuiyan and Naser [15] investigated the radiative and convective heat transfer of pulverized coal combustion. In that study the experimental results were compared against CFD simulation values. The study shows that the numerically calculated results exhibited a reasonable agreement with the measured surface incident radiation (SIR) in the furnace radiative wall. Mayr et al. [16] compared their numerical modeling results to a laboratory scale oxy-fuel experiment. In their study, oxygen concentrations were varied in the oxidizer and mixed with natural gas. The results compared well with experimental measurement points. Yin and Yan [17] also present a state-of-the-art review of pulverized fuel oxy-combustion modeling. The authors identify a variety of future research needs for modeling, which include improved particle radiation models, chemical kinetics, and investigation into advanced oxy-fuel technologies on a fundamental basis among other topics.

Based on a survey of literature a majority of the research works performed on oxy-fuels, experimental and modeling, are concentrated on using coal or oxy-fuels in a Rankine type cycle configuration. It is also feasible that oxy-combustion could be used in a Brayton cycle driven power system that takes advantage of the higher temperatures and produces power more efficiently than existing systems. Zhang and Lior [2] proposed that an oxy-fuel power generation system has potential of achieving up to a 52% net efficiency. This value incorporates the power consumption required for the air separation unit. Sanz et al. [18] conducted a study on 400 MW Semi Closed Oxy Fuel Combustion-Combined Cycle. The study showed that an efficiency of 50% could be achieved for this type of power generation system. In some other papers, it has also been proposed that introducing the working fluids in this cycle in the supercritical phase could further enhance the overall cycle efficiency and reduce the power plant physical footprint [17–24]. One type of system has been deemed the so-called directly heated oxy-fuel supercritical power generation system and is the focus of the current paper. In directly heated cycles the combustion process directly heats the turbine working fluid. The fuel and oxidizer are pressurized to supercritical fluids utilizing a compression system. Afterwards, the fuel and oxidizer are combusted at a pressure ranging from 20 to 30 MPa and delivered to the turbine for the power generation. This high pressure is usually used since directly heated systems ideally have all of the combustion products, H_2O and CO_2, at a supercritical state. Due to the very high power density, the directly heated supercritical CO_2 cycle has the ability to extract more power from a turbine at higher temperatures [24]. McClung et al. [20] are one of the few investigators that focus on directly heated supercritical gas turbines. According to McClung et al. [20], directly fired supercritical oxy-combustion cycles using the recompression closed Brayton cycle has potential to achieve a 64% thermal efficiency and 52% net plant efficiency. The combustion chamber pressure for the system analyzed is 29 MPa and the turbine inlet temperature is 1493 K.

Another type of system that can be employed to extract power from supercritical fluid is the indirectly heated power generation technique [19,21–23]. Although not the focus of this paper, it is useful to consider the applications of the indirectly heated power cycle since much more literature is available on this topic. For example, similar analysis of supercritical systems can be performed for different fluid properties at supercritical conditions regardless of the power extraction method. Oh et al. [23] used the Lee-Kesler-Plocker equation of state to investigate an indirectly heated supercritical CO_2 gas turbine, hence a similar methodology could be used for a directly heated system [23]. In an indirectly