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Effect of operating pressure and fuel moisture on net plant efficiency of a staged, pressurized oxy-combustion power plant

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ABSTRACT

The immediate need for a high efficiency and low cost carbon capture process has prompted the recent development of pressurized oxy-combustion. With an increase in combustion pressure, the dew point of the flue gas is increased, allowing for effective integration of the latent heat of flue gas moisture into the Rankine cycle. This increases the net plant efficiency and reduces costs. The Staged, Pressurized Oxy-Combustion (SPOC) process further enhances the efficiency and reduces costs by reducing the recycle of flue gas to near zero. Fuel staging and a novel boiler/burner design are used to control temperature and heat flux. Compared to a first generation oxy-combustion process, the SPOC process results in an increased net plant efficiency of about 6 percentage points. In this work, the effects of operating pressure and fuel moisture content on the net plant efficiency are discussed. It is shown that the effect of pressure is small for pressures higher than about 16 bar, while the effect of fuel moisture is 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 dramatic. The effect of slurry feeding of coal on plant efficiency is discussed.

1. Introduction

Carbon dioxide emitted from coal-based power plants is one of the largest sources of greenhouse gas emissions. Nonetheless, the large reserves and ubiquitous distribution of coal, and the ability to produce power on demand render it an irreplaceable resource, especially in terms of energy security and geopolitical stability. In order to minimize the emission of greenhouse gases, while still maintaining the ability to utilize this vast resource, a number of methods to capture the carbon dioxide, and subsequently utilize or sequester it, have been proposed. Even with broad international support for carbon capture, utilization and sequestration (CCUS), implementation has been very limited, primarily due to the high energy and cost penalties associated with such systems (Koelbl et al., 2014; Mendelevitch, 2014; Wall et al., 2011).

Oxy-coal combustion, where coal is combusted with a mixture of oxygen and recycled flue gas to produce a concentrated stream of CO_2, is considered as one of the most desirable approaches for carbon capture from coal based power plants. Still the cost of electricity is increased about 70% and the efficiency reduced about 25% (DOE/NETL, 2008; McDonald et al., 2007). Pressurized oxy-combustion has recently gained attention as a means to reduce the cost and energy penalties of carbon capture (Zheng et al., 2010; Hong et al., 2009; Gopan et al., 2014). Pressurization of the combustion process leads to pressurized flue gas directly. This offers a number of advantages, the primary one being that the dew point of flue gas is higher than at atmospheric pressure, providing the opportunity to condense the moisture at a sufficiently high temperature such that the latent heat of condensation can be integrated into the Rankine cycle (steam cycle). The optimal pressure has been studied for two different systems—one developed by Babcock Power and Thermo-Energy (Zheng et al., 2010) and the other, a flameless combustion system, developed by ITEA and ENEL (Zebian et al., 2012). Pressures ranging from 6 bar to 80 bar have been considered, and the optimal pressure has been found to be system dependent (Zheng et al., 2010; Zebian et al., 2012; Hong et al., 2010; Zebian et al., 2013).

First generation oxy-combustion processes require recycling 60–80% of the flue gas back into the furnace in order to maintain temperature and heat flux in ranges similar to air-fired combustion. Several groups have considered reducing the recycle ratio in order to minimize the capital and operating costs, as well as the efficiency loss associated with the recycle of such large amounts of flue gas (Nikzat et al., 2004; Becher et al., 2011; Kobayashi and

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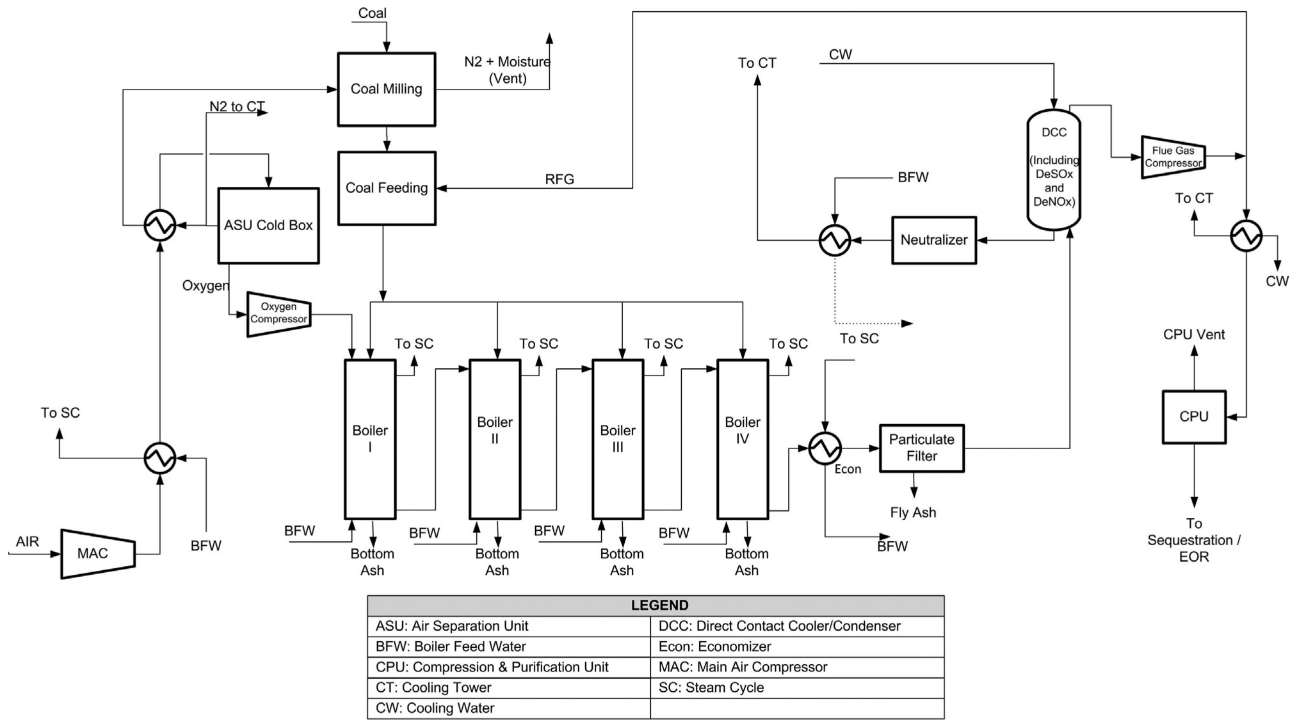

Fig. 1. SPOC Process Flow Diagram (Gas Side) (Gopan et al., 2014).

Bool, 2011; Patrick et al., 2011). Kobayashi and Bool have reported that a number of air-fired industrial furnaces have been converted to full oxy-firing without recycle (Kobayashi and Bool, 2011). Even though in most cases these modifications have resulted in better performance, they have only been demonstrated for industrial furnaces and boilers with much lower fuel (thermal) input, and steam pressures and temperatures than utility boilers. A summary of the efforts for combustion of coal at high oxygen concentration (low recycle) is given in (Kobayashi and Bool, 2011). The authors noted that none of these efforts have made a significant contribution in controlling the heat flux to acceptable levels for utility boiler applications. They proposed potential methods for tackling the challenge of high heat flux, but there have been no subsequent reports in the literature on the ability of these proposed methods to control heat flux.

Recently, a novel approach to pressurized oxy-combustion has been introduced, namely, the Staged Pressurized Oxy-Combustion (SPOC) process. A simplified process flow diagram is shown in Figs. 1 and 2. The performance analysis of a conceptual 550 MWe power plant based on the SPOC process has been conducted (Gopan et al., 2014). In this process, the recycle of flue gas is minimized and the fraction of radiative heat transfer (in contrast to convective heat transfer) is increased while still maintaining an optimal wall heat flux. This is achieved by staging the delivery of pulverized coal, which is fed using dry pneumatic feeders, such as those utilized in Siemens (Morehead, 2008), Shell and Mitsubishi (Maroto-Valer, 2010) gasifiers. As can be seen from Fig. 1, in the SPOC process nearly all the oxygen required for combustion is supplied to the first stage, while the supply of fuel is staged in multiple boilers. This creates an oversupply of oxygen in the first stage, which acts as a diluent and keeps the mean temperature of this stage similar to conventional oxy-combustion. The exhaust of stage 1 is then fed to stage 2, where more fuel is added and the excess oxygen in the exhaust of the first stage is utilized for combustion. The cooled products of combustion from stage 1 act as diluent for stage 2 and help to control temperature. This process continues in subsequent boilers until nearly all the oxygen is consumed, eliminating the need for recycled flue gas to control temperature. By utilizing the excess oxygen, boilers and burners may be designed to avoid potentially harmful peaks in heat flux and flame impingement on boiler tubes.

As described above, since the flue gas in the SPOC process is at high pressure, the latent heat of the flue gas moisture can be integrated into the steam cycle. In this process, the flue gas, after being cooled down in an economizer and after particulate removal, goes to a direct contact column (DCC), which is a counter-flow column with cooling water flowing from the top and flue gas flowing from the bottom. In the DCC, the flue gas moisture is condensed, and sulfur and nitrogen oxides are removed due to their mutual interactions at high pressure (Hong et al., 2009; White et al., 2013; Stanger et al., 2014). After the DCC, the flue gas is further purified and compressed to pipeline requirements in the compression and purification unit (CPU).

Recently, Électricité de France (EDF) compared the SPOC process with an alternative pressurized oxy-combustion process, as well as atmospheric pressure oxy-combustion and air-fired combustion (Hagi et al., 2014). The goal was to understand the advantages and disadvantages of the different approaches to carbon capture from an energetic and exergetic standpoint. It was shown that the increase in radiative heat transfer relative to convective heat transfer in SPOC increased the overall exergy transfer from the flue gas to the steam cycle, increasing the plant efficiency. Also, with the reduced recycle, the auxiliary load was lower in the SPOC process thereby increasing the net plant efficiency as well. Furthermore, the dry (surface-dry) feeding of coal in the SPOC process creates opportunity for increased heat integration from other sources of low-grade heat such as the air separation unit (ASU) and oxygen compressors. As will be shown, adding excess moisture, for example by introducing the coal as slurry, reduces the plant efficiency even if all the moisture is condensed.

The process modeling results of SPOC shows a 6 percentage point increase in efficiency over 1st generation oxy-combustion power plant models (Gopan et al., 2014; Hagi et al., 2014) and a 4 percentage point increase in efficiency over the ISOTHERM process