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Comparative assessment of sub-critical versus advanced super-critical oxyfuel fired PF boilers with CO_2 sequestration facilities

Sina Rezvani *, Ye Huang, David McIlveen-Wright, Neil Hewitt, Yaodong Wang

NICERT, School of Built Environment, University of Ulster, Newtownabbey, BT37 0QB, UK

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Abstract

This work focuses on the techno-economic assessment of bituminous coal fired sub- and super-critical pulverised fuel boilers from an oxyfuel based CO_2 capture point of view. At the initial stage, two conventional power plants with a nominal power output of above 600 MWe based on the above steam cycles are designed, simulated and optimised. Built upon these technologies, CO_2 capture facilities are incorporated within the base plants resulting in a nominal power output of 500 MWe. In this manner, some sensible heat generated in the air separation unit and the CO_2 capture train can be redirected to the steam cycle resulting in a higher plant efficiency. The simulation results of conventional sub- and super-critical plants are compared with their CO_2 capture counterparts to disclose the effect of sequestration on the overall system performance attributes. This systematic approach allows the investigation of the effects of the CO_2 capture on both cycles. In the literature, super-critical plants are often considered for a CO_2 capture option. These, however, are not based on a systematic evaluation of these technologies and concentrate mainly on one or two key features. In this work several techno-economic plant attributes such as the fuel consumptions, the utility usages, the plant performance parameters as well as the specific CO_2 generation and capture rates are calculated and weighed against each other. Finally, an economic evaluation of the system is conducted along with sensitivity analyses in connection with some key features such as discounted cash flow rates, capital investments and plant efficiencies as well as fuel and operating costs.

Keywords: Air separation unit (ASU); Oxyfuel-based CO_2 capture (O_2/CO_2); Sub-critical (SUBPF) and advanced super-critical pulverised fuel boiler (ASCPF); Techno-economic analysis

1. Introduction

In order to reduce the greenhouse gas emissions from coal-fired power plants, state of the art technologies with their conventional gas cleaning systems need to be further upgraded towards dependable and economically viable CO_2 capture facilities. As a dominant and widely accepted technology, pulverised fuel boilers with sub-critical steam cycles have come under scrutiny when it comes to obtaining higher efficiency levels. This characteristic is particularly significant in the case of CO_2 capture allowing the compensation of increased internal power consumptions caused by additional utilities such as air separation and CO_2 compression units. The operation of advanced super-critical steam cycles is geared to improve the overall power plant performance attributes and seem to be a reasonable and practical solution for the compensation of efficiency losses. On the other hand, this emerging technology as a prospective alternative to the sub-critical steam cycles suffers the preconceived development phase mainly characterised by a more frequent incidence of technical failures and lower partial load operating ranges. As part of an ongoing system progression, engineers utilise and develop novel components and advanced materials to enhance plant reliability and flexibility, which can only be obtained at higher costs.

* Corresponding author. Tel.: +44 (0)28 90366923; fax: +44 (0)28 70327004.
E-mail address: s.rezvani@ulster.ac.uk (S. Rezvani).

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To address the above-mentioned dichotomy, a techno-economic assessment is carried out within this paper in connection with sub-critical and advanced super-critical bituminous coal fired pulverised fuel plants. For this assessment, the ECLIPSE chemical process simulation package was utilised to emulate the real process. The nominal power outputs for this case study is selected at slightly above 600 MWe for the conventional systems and at 500 MWe net for the sub-critical and super-critical plants with CO_2 capture facilities. The process simulation of the conventional plants without the CO_2 capture as the base technology is required for assessing the impact of the CO_2 capture for sub-critical and super-critical cycles.

The CO_2 sequestration is achieved through an oxyfuel firing approach supported by a two-stage CO_2 recirculation and subsequent CO_2 cleaning and compression facilities. A cryogenic air separation unit is used to generate oxygen at a purity level of 95%. The CO_2 leak is assumed at around 5%. The CO_2 leaving the plant is further purified removing uncondensable constituents and water vapours through a cryogenic system as part of the CO_2 compression train. The final gas condition ready for the transport through pipelines lies at above 95% purity pressurised at 110 bar and cooled to normal temperature.

Although the sub-critical cycles are generally accepted to be a low risk option, over the last two decades, however, operational experiences and developments in advance super-critical systems have resulted in similar reliabilities. Today, sub-critical plants dominate the market worldwide by a large margin. This is mainly due to a proven and long-term record of reliability. The power plant performance, however, improves significantly in connection with the super-critical cycle. The higher capital cost of super-critically operated plants – mainly due to high quality materials to support the super-critical steam condition – is marginalised by lower gas cleaning costs as well as lower fuel and ash-handling expenses as a result of reduced fuel consumption. Additionally, the higher power plant efficiency of the super-critical cycle results in favourable techno-economic attributes. Over several decades, engineers have been making constant efforts to optimise the overall power plant designs of the super-critical and ultra-critical cycles ensuring improved technical and economic plant operations. In the near future, advanced super-critical boilers will gain more acceptance as currently observable. This trend makes this type of cycle a good candidate for oxyfuel-based CO_2 sequestration systems if the techno-economic frameworks are propitious such as acceptable plant capacity factor, reasonable operating and maintenance works as well as adequate plant overall costs.

This paper is structured into three main parts. The next section looks into the technical issues of sub- and super-critical cycles without any CO_2 capture as the reference plants. The subsequent chapter investigates the integration of the oxyfuel-based CO_2 capture within the reference plants. The last section analyses the economics of CO_2 capture in connection with the above-mentioned cycles.

1.1. Methodology

For the assessment of the selected plants, the ECLIPSE process simulation package is used. This software was initially intended for the use of power plant research projects of the European Commission. However, since its development, it has been used for simulating many different chemical and engineering processes. Through a large number of real industrial process simulations, ECLIPSE has been validated over the years and gained recognition worldwide among research institutes, governments and industrial companies. In the literature in connection with many projects and research activities such as the JOULE clean coal technology [1] or advanced coal fired utility boilers [2], abundant sources of information can be found, where ECLIPSE simulation package is described in more detail.

At the initial stage, process flow diagrams composed of modules and streams are generated within ECLIPSE. After specifying the stream inputs and technical features of individual modules, the mass and energy balance is determined via enthalpy calculations for each stream. This is achieved by converging the information specified in the compound database, as well as in the input streams and modules. The latter contains details such as efficiencies, stream manipulations and splits in reference to individual power plant components with the exception of chemical reactors, whose output streams are specified through the yield and elemental balance. The information gained during this second of simulation forms the base for identifying critical components within the plants subjected to extreme physical and chemical exposure. In the third stage, the package computes the amount of energy consumed by individual utilities and compounds and provides the power plant net output. This simulation module has access to a utility database, which predominantly contains information about the process utility systems, the electricity supply options and the mechanical efficiency of integrated modules such as turbines, pumps and compressors. The simulation of an air separation unit and a CO_2 compression train is also performed using ECLIPSE.

Finally, the economic viability of the examined systems is evaluated. In this phase of work, the breakeven-electricity selling price is computed using the net-present value considering all the essential financial factors such as the interest rate payments, annual operating and maintenance costs as well as soft-costs and outlays incurred as a result of plant construction and plant commissioning time along with the main cost contributors capital investment and annual fuel expenses. Since the economics cannot be summarised in clear-cut values and depend on multivariate factors, sensitivity analysis are performed in connection with several key factors such as discounted cash flow rates, capital investments and power plant efficiencies as well as fuel price levels and operating costs. To disclose the effect of