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Thermodynamic assessment of an integrated MILD oxyfuel combustion power plant

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ABSTRACT

The paper presents the advantages of a new boiler solution for the supercritical power plant with CO_2 capture. The MILD oxyfuel combustion (MOFC) combines the advantages of MILD (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. MOFC application could increase the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. Thermodynamic analysis of an integrated MOFC power plant with CO_2 capture are presented. The data concerning the new design of the boiler are obtained from CFD modelling. Two case studies are performed, and in each of them three configurations of supercritical power plant are modelled. First two are the reference power plants, including the conventional power plant without CO_2 capture and oxyfuel combustion power plant with CO_2 capture. The third case is the MOFC boiler application within the same power plant. The thermodynamic parameters are compared, and detailed study of energy efficiency penalty is presented. Based on the presented results it can be noticed that the application of the MOFC technology allows to increase the overall net energy efficiency by about 2% points. Additionally the usefulness of the proposed system approach (based on input-output analysis) for the energy analysis of complex energy systems have been proven.

1. Introduction

In recent years interest has grown in the carbon capture and storage technologies (CCS) as the possible technology to mitigate the CO_2 emissions from both power sector and other industry branches. Generally three types of CCS technologies can be distinguished, viz. post-combustion, pre-combustion and oxy-fuel combustion (Fig. 1), which were briefly compared within Table 1.

The presented paper focus on the MILD oxyfuel combustion (MOFC) technology, which is a next step within clean coal technologies, that combines the advantages of MILD (moderate and intensive low-oxygen dilution) combustion and oxyfuel combustion for the purpose of an effective CO_2 capture from fossil fuel based power generation. The CO_2 transport and storage (or utilization) are important and indispensable components of CCS, thus within this article the impact of the CO_2 transport and storage on the energy efficiency of the whole CCS chain is also discussed.

The oxyfuel capture technology is based on usage of high-purity oxygen in the combustion process instead of atmospheric air. Therefore flue gases have a high concentration of CO_2 (without nitrogen dilution), which allows to evade chemical post-combustion processes. Due to the limited adiabatic temperature of combustion part of CO_2 must be recycled to the boiler in order to maintain a proper flame temperature. Power plants constructed in this technology must comprise two main additional parts - the air separation unit (ASU) and the carbon dioxide processing unit (CPU), which latter can be divided into CO_2 purification and CO_2 compression units. Oxyfuel combustion is also taken into consideration in already existing retrofitting power plants, by adding ASU and CPU and adequate upgrading in the boiler island. Due to the higher cost of producing electricity, caused by implementing the

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Nomenclature

Main symbols

A	matrix of the coefficients of the consumption of energy carriers and materials
a_{ij}	coefficient of consumption of energy carriers and materials
D	vector of external supplies
D	external supply
F	matrix of the coefficients of the by-production
f_{ij}	coefficient of by-production of energy carriers or materials
G	column vector of the main production
G	main production
I	unit matrix
K	column vector of the final production
K	final production

Subscripts and superscripts

ch	chemical
D	external supply not supplementing the main production
DG	external supply supplementing the main production
el	electricity
F	by-product
FG	by-product supplementing the main production
G	main product

Abbreviations

ASU	Air Separation Unit
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CPU	CO_2 Processing Unit
FGQC	Flue Gas Quality Control
HHV	Higher Heating Value
LHV	Lower Heating Value
MILD	Moderate and Intensive Low-oxygen Dilution
MOFC	Moderate and intensive low-oxygen dilution OxyFuel Combustion
OFC	Oxy-Fuel Combustion
OSA	Oxy System Analysis
p.p.	percentage point
REF	Reference
TRL	Technology Readiness Level

CCS technology, process integration must be taken into consideration in order to lower the cost of carbon dioxide capture. One of the main ways of integration is the utilization of heat from compressor cooling systems concerning ASU and CPU with the steam cycle. The air separation unit and CO_2 purification unit are usually based on the cryogenic distillation system, because this technology is on the proper level of development to ensure the required performance of large-scale oxy-fired power plants with carbon dioxide capture. The utilization of nitrogen (e.g. drying of fuel) and application of the central water cooling system in individual cooling systems of the compressors are further examples of an integrated project.

Major challenges for current state-of-the-art oxyfuel combustion power plants are low-cost oxygen supply, developing high-temperature materials in new constructions and conversion schemes for existing air-fired power plants. Also preventing air infiltration is essential for both new and retrofitted power plants. Most of the worlds R&D project focus around new technologies for oxygen production, like e.g. membrane air separation units that can be integrated with boilers, for energy and cost effective oxygen supply. But within the oxyfuel combustion technology, there are other processes that are responsible for the net energy penalty associated with CO_2 capture and compression. Nowadays the drop of the net energy efficiency is predicted to be around 8% points compared to the reference air-fired supercritical power plants.

Fig. 2 presents, the estimated within an interdisciplinary MIT study [5], parasitic energy requirements for oxyfuel pulverized coal generation with CO_2 capture. Both, air-fired and oxyfuel combustion power plants, have supercritical steam cycle. The 3% point efficiency increase, for oxyfuel combustion compared to the air-fired power plant, is due to the improved boiler efficiency and reduced energy consumption for flue gas desulphurization. As mentioned already, the most significant net energy efficiency penalty is associated with the oxygen production. Within the other sources of energy efficiency drop, we may identify mainly the electricity consumption associated with the recycle of CO_2 to the boiler.

MILD oxyfuel combustion application could increase further the efficiency of the boiler, increase the purity of the CO_2 in flue gases and reduce energy consumption for the recirculation of CO_2. It affects the overall net energy efficiency penalty associated with the CO_2 capture in comparison to the oxyfuel combustion technology. MOFC boiler design gives also an opportunity to include the membrane air separation units with heat integration on required high temperature levels. Thus, within this paper, the preliminary thermodynamic analysis of an integrated MOFC power plant with CO_2 capture is presented, in order to investigate the potential of this technology. The successful implementation of CCS, and thus MOFC technology, will depend on economical factors, mostly the cost of electricity. Although post-combustion technology, based on chemical absorption by means of amine solutions, is now the only mature technology of CO_2 capture [2], nevertheless it has been considered that other CCS technologies are still considered, and some of them (as oxyfuel combustion) are even more promising [5].

2. Development pathway of MILD oxyfuel combustion

Within this section the technology development pathway have been presented, from the point of view of the replacement of air with oxygen in the combustion process. Several concepts are briefly presented and discussed, pointing out the relevance to the development of the MILD oxyfuel combustion technology.

2.1. Mixed air and oxygen combustion

Within the oxyfuel combustion several technological options and configurations were investigated in the literature. Most of them assumed elimination of the air in the combustion process in order to eliminate the dilution of the flue gases, so that the high concentration of CO_2 can be obtain (e.g. after just dehydration). Within [6] authors proposed a novel approach, in which the air can be used to carry the coal from the mills to the boiler (as in air-fired power plants), while oxygen is added to the secondary recycle flow and directly to the combustion zone. The presented concept, referred as CO2RE, could practically eliminate the problem with the primary recycle and air leakage into the CO_2 processing system.