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Effect of the CO_2 enhancement on the performance of a micro gas turbine with a pilot-scale CO_2 capture plant

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ABSTRACT

Gas turbines are a viable and secure option both economically and environmentally for combined heat and power generation. Process modelling of a micro gas turbine for CO_2 injection and exhaust gas recirculation (EGR) is performed. Further, this study is extended to assess the effect of the CO_2 injection on the pilot-scale CO_2 capture plant integrated with a micro gas turbine. In addition, the impact of the EGR on the thermodynamic properties of the fluid at different locations of the micro gas turbine is also evaluated. The micro gas turbine and CO_2 injection models are validated against the set of experimental data and the performance analysis of the EGR cycle results in CO_2 enhancement to 5.04 mol% and 3.5 mol%, respectively. The increased CO_2 concentration in the flue gas, results in the specific reboiler duty decrease by 20.5% for pilot-scale CO_2 capture plant at 90% CO_2 capture rate for 30 wt.% MEA aqueous solution. The process system analysis for the validated models results in a much better comprehension of the impact of the CO_2 enhancement on the process behaviour.

1. Introduction

The energy trend across the globe is changing due to the overwhelming concern regarding emission of greenhouse gases from the power generation sector (IEA, 2012). The contribution of the conventional power generation system, including coal- and natural gas-power generation, is in the gradual transition stage towards more sustainable systems, as towards low or zero carbon emission emitters. However, natural gas-fired power plants are a secure and viable option both economically and environmentally as it results in less oxides of carbon, nitrogen and sulphur in comparison to coal-fired power plants. Increased urbanization results in an escalated power demand and thus have led to a shift to natural gas-fired power plants around the globe to meet both the increasing demand and reduced emissions targets. In addition, post-combustion carbon capture technology needs to be integrated with a natural gas-fired power plant to reduce the carbon emissions with the most mature technology, the amine absorption system. However, the integration of the natural gas-fired power plant with amine-based carbon capture results in a major energy penalty due to the low CO_2 concentration in the exhaust gas from a natural gas-fired power plant. Literature reports various innovations to the natural gas-fired power generation system (Heppenstall, 1998; Poullikkas, 2005); however, most of them deal with efficiency enhancement rather than the enriching of the exhaust gas with CO_2. However, exhaust gas recirculation (Earnest, 1981) is the one of the innovative solutions in dealing with the low CO_2 concentrations in the exhaust gas from natural gas-fired power plants.

The benefits of the EGR system are well known as it enhances the CO_2 concentration of the exhaust gas and reduces the exhaust gas flow rate (Ali et al., 2014, 2015b). Both of these benefits results in the reduced penalty on the integration of the amine-based carbon capture system with the natural gas-fired power generation plant in EGR mode. The specific flue gas flow rate of a gas turbine system is much

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Nomenclature

CCS	Carbon capture and storage
CDT	Compressor discharge temperature
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
DLN	Dry low NO_x
EGR	Exhaust gas recirculation
H	Head
m	Mass flow rate
MGT	Micro gas turbine
N	Rotational speed
P	Pressure
PACT	Pilot-scale advanced capture technology
r	Pressure ratio
R	Universal gas constant
R&D	Research and development
T	Temperature
TIT	Turbine inlet temperature
TOT	Turbine outlet temperature
UHC	Unburned hydrocarbons
z	Compressibility factor
γ	Ratio of specific heats (c_p/c_v)
δ	Pressure ratio
θ	Temperature ratio

Subscripts

cr	Corrected
in	Inlet
out	Outlet
ref	Reference condition

higher at about 1.5 kg/MW in comparison to a steam boiler system at about 0.95 kg/MW and EGR can considerably reduce the flue gas flow rate, thus resulting in a lower load on the amine-based CO_2 capture system when integrated (Jonshagen et al., 2010). The decrease in the mass flow can be accounted for by the changing temperature at the compressor inlet since the recycled stream is at a higher temperature, and to achieve the same combustor temperatures, a lower amount of cooler air is required (Li et al., 2011a). The application of the EGR results in the increased MACH numbers at the inlet and outlet tips of the compressor rotor due to the changes in the thermodynamic properties of the fluid stream (Jonshagen et al., 2010) however, this increase will not pose severe issues to the turbo machinery (Jonshagen et al., 2011). In addition, the increase in the CO_2 concentration in the working stream of the gas turbine, due to the EGR, results in the change of the thermodynamic properties of the fluid stream, both in the turbo machinery and the combustion section of the gas turbine (Ali et al., 2015b). Also, the recycled stream results in a higher water content at the combustor inlet, which can be controlled by the condenser present in the recycle loop (Ali et al., 2015a). Further, the injection of the recycle stream can be done at various locations in the gas turbine, resulting in different control algorithms due to the imbalance on the shaft (Ali et al., 2015a). An important consideration for EGR operation is that the maximum amount of the exhaust gas to be circulated is still undefined, as with an increase in the EGR, the combustion kinetics, stability, and emissions issues arise. The increase in EGR causes O_2 starvation at the combustor inlet with issues in terms of flame stability and increased emissions of unburned hydrocarbons (UHC) and CO, when O_2 concentration falls to 14 mol% at the combustor inlet (Ditaranto et al., 2009; Evulet et al., 2009). Moreover, the experimentation with a DLN F-class gas turbine combustor shows the stable operation for EGR up to 35% (ElKady et al., 2009). Hence, the recommended O_2 concentration at the combustor inlet should be higher than 16 mol% to have a stable combustion operation in the gas turbine system with EGR (Bolland and Mathieu, 1998; Ditaranto et al., 2009; ElKady et al., 2009; Evulet et al., 2009). Further, modifications that are recommended in the literature for an EGR applicability include; changes in the premixedness, control system and variation in the design of the pilots for the burners to reach higher levels of the EGR percentage (ElKady et al., 2009). Technical modifications to the combustor design may result in more oxidant injection or a pure oxygen stream with different distribution levels which will result in a higher EGR percentage and much higher CO_2 levels in the flue gas. In addition, the guarantee issues from the gas turbine manufacturers should be the priority for the safe operation and redesign of the combustor and/or the whole gas turbine structure.

Work has been performed regarding the effect of the EGR on the performance of gas-fired power plants integrated with post-combustion capture systems with emphasis on the energy penalty and reduction in cost of the combined system (Belaissaoui et al., 2013; Biliyok et al., 2013; Biliyok and Yeung, 2013; Botero et al., 2009; Canepa and Wang, 2015; Canepa et al., 2013; Jonshagen et al., 2010, 2011; Li et al., 2011a,b; SipÃķcz and Assadi, 2010; SipÃķcz et al., 2011; Sipöcz and Tobiesen, 2012; Yu et al., 2013). However, most of the work was performed on commercial-scale natural gas-fired power plants operated with EGR and then its integration with a post-combustion capture plant.

This paper focuses on the micro gas turbine which is a low emission, reliable and efficient combined heat and power generation system that competes with the combined heat and power reciprocating engines. Further, the micro gas turbine (MGT) is a good and accessible option for research purposes and the performance outcomes can provide recommendations for the commercial-scale gas turbines. However, the CO_2 concentration in the exhaust gas of the micro gas turbine is much lower, it ranges from 1.5 to 1.8 mol% while the commercial-scale natural gas-fired turbines have CO_2 concentrations in the range 3.8–4.4 mol% (Canepa et al., 2013; Li et al., 2011a,b; Sipöcz and Tobiesen, 2012). Regarding MGT, the impact of the EGR on the emissions and performance for different kinds of fuel by analysing through CFD modelling, is reported in the literature (Cameretti et al., 2009, 2013). It is important to note that some work on the effect of the EGR on the performance, and sensitivity analysis of the ambient temperature for the MGT with EGR have been reported in the literature (Akram et al., 2013; Ali et al., 2014, 2015b; Majoumerd et al., 2014; Nikpey et al., 2014). Further, the literature reports the varying optimum EGR from 40 to 55% through different process modelling tools.

1.1. *Novelty*

In this paper, the EGR has been investigated by injecting CO_2 to the MGT inlet which is further integrated with the amine-based CO_2 capture plant. The performance evaluation of MGT and amine-based CO_2 capture plant for CO_2 enriched working stream will result in a better understanding of the effect of the EGR and assist in reaching the optimum conditions for operation.

Due to the limited literature found in this field, an extensive study needs to be performed on the effect of the CO_2 on the performance of the MGT, along with the effect on the amine-based CO_2 capture plant. Studying the behaviour of the MGT, along with CO_2 injection in full detail, is necessary to fully comprehend the optimum performance of the MGT in the innovative mode of the EGR operation. Hence, this study focuses on the evaluation of the impact of these parameters on the performance of the MGT and amine-based CO_2 capture plant for CO_2 injected and/or EGR operated MGT. The impact of the CO_2 enrichment on the thermodynamic properties of the working stream at different locations of the MGT is also investigated to assess the behaviour of the innovative EGR cycle.

This paper is structured as follows. In Section 2, the process description along with the modelling strategy is described in detail and also the methodology is presented. In Section 3, the validation of the MGT for base case and CO_2 injection is presented along with the set of comprehensive data and then the modelling of the MGT with EGR is presented. Further, the effect of the EGR on the thermodynamic properties of the working stream at different locations of the MGT is evaluated. In addition, the impact of the CO_2 injection on the pilot-scale CO_2 capture