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ELSEVIER
Energy 32 (2007) 549–567
ENERGY
www.elsevier.com/locate/energy

CO_2 abatement by co-firing of natural gas and biomass-derived gas in a gas turbine

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Received 1 November 2005

Abstract

In this work, a possible way for partial CO_2 emissions reduction from gas turbine exhausts by co-firing with biomass is investigated. The basic principle is the recirculation of a fraction of the exhausts (still rich in oxygen) to a gasifier, in order to produce syngas to mix with natural gas fuel. As biomass is a CO_2 neutral fuel, the fraction of replaced natural gas is a measure of CO_2 removal potential of the powerplant.

The investigated solution considers the conversion of solid fuel to a gaseous fuel into an atmospheric gasifier, which is blown with a recirculated fraction of hot gas turbine exhausts, typically still rich in air. In this way, the heat content of the exhausts may be exploited to partially sustain the gasification section.

The produced syngas, after the tar removal into the high temperature cracker, is thus sent to the cooling section, consisting of three main components: (I) gas turbine recuperator, (II) heat recovery steam generator and (III) condensing heat exchanger to cool down the syngas close to the environmental temperature before the subsequent recompression and mixing with natural gas fuel into the combustion chamber. The water stream produced within the condensing heat exchanger upstream the syngas compression is vaporised and sent back to the gasifier.

If very limited modification to the existing gas turbine has to be applied in order to keep the additional costs limited, only a relatively reduced fraction of the low calorific value syngas may be mixed with natural gas. The analysis at different levels of co-firing has shown that no appreciable redesign has to be applied to the target GE5 machine up to 25–30% (heat rate based) renewable fraction. With an accurate heat recovery from the cooling/cleaning system of the syngas, the same levels of efficiency of the original machine have been achieved, in spite of the relatively large power consumption of the syngas recompression. Very interesting results have been obtained within the 10–30% range of biomass co-firing, with CO_2 removal levels between 30% and 50% with reference to the values of the base GE5 gas turbine powerplant.

The economic analysis has shown that, in spite of the high investment required for the syngas fuel production chain (gasifier, coolers, cleaners and fuel compressor), approximately at the same level of gas turbine itself, there is an interesting attractiveness due to the possibility of selling high-value green certificates and CO_2 allowances, which reduce the payback time to 2–4 years.

The uncertainty on the calculated economic parameters are greatly influenced by the uncertainty on actual biomass availability and yearly working time of powerplant, whereas off design operation, which affects mainly the uncertainty of compressor and turbine efficiency, is mainly reflected on the uncertainty of electric power output and efficiency.

Keywords: Gasification; Co-firing; Gas turbine; Biomass; Green certificates; CO_2 emissions reduction

1. Introduction

The Kyoto Protocol subscription led many countries to make efforts toward the research and proposal of systems and techniques for CO_2 capture and sequestration from powerplants. Most of these studies investigate the field of massive CO_2 emissions capture (80% plus), by applying pre or post combustion technologies [1–11]. The proposed solutions often imply relevant changes in existing turbo-machinery equipment, which are highly expensive and generally discourage the electricity providers in taking

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0360-5442/$ - see front matter
doi:10.1016/j.energy.2006.07.026

Nomenclature

AF_{st} actual air/fuel ratio
AF_{act} stoichiometric air/fuel ratio
a_{GT} sound speed at inlet turbine (m/s)
α moles of H per mole of biomass
β moles of O per mole of biomass
$\Delta\Phi_{GE5}$ variation of dimensional flow coefficient at turbine inlet relative to the nominal GE5 design value
η_{GT} GT efficiency
η_{EL} net electric efficiency
η_{film} film cooling effectiveness
η_{GEN} electric generator efficiency
C_{quota} price of CO_2 allowance per ton of CO_2 avoided
ER equivalence ratio = AF_{act}/AF_{st}
ε_H blade cooling effectiveness
f fraction of exhausts recirculated to the gasifier
Φ_{GE5} nominal dimensional flow coefficient of the target GE5 gas turbine (m^2)
Φ_{GT} dimensional mass flow coefficient at turbine inlet (m^2)
F_{ren} fraction of gas turbine heat rate provided with syngas fuel
GC price of green certificates (€/kWh)
G_{green} yearly incomes from sale of green certificates (€)
G_{CO_2} yearly incomes (or missed outcomes) due to CO_2 quota (€)
G_{CH_4} yearly savings, over the basic GT, due to reduced natural gas consumption (€)
H_P total energy of products (kW)
H_R total energy of reactants (kW)
h_Y yearly number of working hours (years)
LHV generic lower heating value (kJ/kg)
LHV_{CC} lower heating value of fuel mixture at combustion chamber inlet (kJ/kg)
LHV_{syn} lower heating value of syngas (kJ/kg)
Lp_{GAS} relative pressure loss ($\Delta p/p$) at the gasifier + tar cracker
Lp_{HRSG} relative pressure loss ($\Delta p/p$) at the heat recovery steam generator (HRSG) + baghouse filter
Lp_{REC} relative pressure loss ($\Delta p/p$) at the GT recuperator
Lp_{SEP} relative pressure loss ($\Delta p/p$) at the condensing heat exchanger (SEP) + scrubber
m_{bio} biomass flowrate (kg/s)
m_{IG} mass flowrate of exhausts recirculated to the gasifier (kg/s)
m_{GT} inlet turbine mass flowrate (kg/s)
$\underline{m}_{steam}$ mass flow of reinjected steam into the gasifier (kg/s)
m_{syn} syngas flowrate (kg/s)
PBT payback time (years)
PR compressor pressure ratio
Q heat added or released to gasifier (kW)
R powerplant size scale coefficient
ρ_{GT} gas density at turbine inlet (kg/m^3)
T_0 reference temperature (K)
T_g gasification temperature (K)
T_{in} gasifier inlet temperature (K)
T_{OSEP} syngas temperature at the SEP outlet (K)
W_{cmain} main compressor power consumption (kW)
W_{csyn} power demand for syngas fuel recompression (kW)

some measures against CO_2 emissions [10,11]. Even the cheapest solutions, aimed to reduce, as far as possible, the redesign of existing equipment (i.e. semi-closed gas turbine cycles SCGT), have shown additional costs of electricity around 60–70% compared to traditional layouts with no CO_2 removal [12,13], even if most recent studies promise to reach the low 30–40% levels [14]. Further unknowns connected to costs of transportation and storage of liquid compressed CO_2 and the related environmental safety made application of CO_2 capture systems unattended [15].

It is well known that renewable fuel sources have, globally, zero CO_2 emissions to the environment, thus they might have an interesting potential to approach the greenhouse issue. On the other hand, their extensive application to existing powerplants often involves deep and expensive modifications to current technologies. The most mature are those involving IGCC, the largest fraction of which are currently fed with coal but might be converted (at least partially) to biomass fuels with no appreciable changes in equipment. They are, anyway, applicable in the field of large power generation, of the order of few hundred MW electric power [16].

The upcoming 2006 CO_2 emissions trading into the European Community should encourage all Member States to provide substantial investments for tackling CO_2 emissions. The market of CO_2 allowances is planned to start by April 2006. Companies covered by the Emissions Trading Scheme need to record and report their CO_2 emissions as of January 2005. They also need to deliver for the first time in April 2006 a sufficient number of allowances to cover emissions during 2005. If a company delivers no allowances—or not enough allowances—a sanction of €40 per non-delivered allowance will be imposed by the Member State. In this way, the adoption of systems with even partial CO_2 emissions reduction potential (15–50%) might lead to a consistent reduction in electricity production costs and encourage companies to make investments for CO_2 abatement. The partial integration of biomass fuels with natural gas implies a proportional reduction of CO_2 emissions, playing, globally, an important role if its application was extended to several powerplants. The co-firing of gas turbines with natural gas and biomass-derived fuel has been a largely investigated