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Concept of hydrogen fired gas turbine cycle with exhaust gas recirculation: Assessment of combustion and emissions performance

Mario Ditaranto[a,*], Hailong Li[b], Terese Løvås[c]

[a] SINTEF Energy Research, Trondheim, Norway
[b] Mälardalen University, Västerås, Sweden
[c] Norwegian University of Science and Technology, Trondheim, Norway

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ABSTRACT

A novel gas turbine cycle concept applicable to power plants with pre-combustion CO_2 capture or integrated gasification combined cycle (IGCC) is presented. These power plants use a hydrogen rich fuel with high reactive combustion properties which makes fuel dilution necessary to achieve low NOx emissions. The proposed novel gas turbine arrangement is set up as to avoid both fuel dilution and its consequent efficiency penalty, and breakthrough in low NOx combustion technology. In this concept, a high exhaust gas recirculation (EGR) rate is applied in order to generate an oxygen depleted working fluid entering the combustor, enough to reduce the high reactivity of hydrogen rich fuels. As a result, the combustion temperature in this environment is inherently limited, thus, keeping NOx formation rate low. A first order assessment of the combustion characteristics under such gas turbine operating conditions is made in the light of a numerical analysis of stability and NOx emissions potential. Both diffusion and premixed types combustor are considered according to the selected EGR rate. It is first shown that the flame stability could be maintained at EGR rates well above the maximum EGR limit found in conventional natural gas fired gas turbines. The study further shows that at these high EGR rates, considerable reductions in NOx emissions can be expected. The conclusion of this first order analysis is that there is a true potential in reducing the efficiency penalty induced by diluting the fuel in power plants with pre-combustion CO_2 capture.

1. Introduction

Hydrogen rich fuels are suitable for gas turbines in three possible applications: (i) the well-established integrated gasification combined cycle (IGCC) without CO_2 capture; (ii) power plants using the pre-combustion CO_2 capture in the carbon capture and sequestration (CCS) context; (iii) power plants in a fully developed renewable energy based society, where hydrogen is used as energy storage in case of excess wind or solar power. Although CO_2 free, the exhaust gas of a hydrogen fired gas turbine contains pollutants known as nitrogen oxides (NOx) which have been strongly regulated for many decades. During combustion of hydrogen, NOx formation is mostly controlled by temperature through the thermal NOx kinetic pathway (also called Zeldovitch'). As the thermal NOx formation is strongly sensitive to temperature, a small increase in the higher range of temperature results in an exponential increase of NOx. In fact, NOx emissions from hydrogen rich fuels have been very well correlated to adiabatic flame temperature both in laboratory scale flame (Ströhle et al., 2006) and gas turbine tests (Todd and Battista, 2000). For example, Cocchi et al. (2008a) were able to model the emissions from a hydrogen fired combustor over a wide range of parameters variation by tuning a model based on the thermal NO mechanism solely.

In modern hydrocarbon based gas turbines, the problem of high temperature regions in the flame is avoided by premixing the fuel and air prior to combustion by using lean premixed burners also known as dry low NOx (DLN) burners. The technology has struggled for many years because the required degree of air – fuel premixing leads to many issues related to combustion stability: flashback, extinction, and thermo-acoustic instabilities (Candel, 2002). The technology is now commercial and the major gas turbine manufacturers offer engines that achieve NOx emissions levels within the regulated values without the need of abatement systems (SCR). However, the application of this technology to hydrogen rich fuels still strives because of the specific characteristics of hydrogen combustion: wide flammability limits, much higher reaction

* Corresponding author. Tel.: +4747670869.
E-mail address: mario.ditaranto@sintef.no (M. Ditaranto).

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rates, preferential diffusion and higher flame temperatures leading to short auto-ignition times and high flame speed (Chiesa et al., 2005). As a consequence, combustion occurs too quickly, before air and fuel have had the time to be adequately premixed, resulting in high temperature and high NOx emissions. The preferred mode of unwanted flame propagation is flashback through the boundary layer (Lin et al., 2013; Eichler et al., 2012), from which the flame dangerously sits in unwanted locations with the risk of component damage. In addition, the flame temperature is higher in hydrogen than in hydrocarbon flames, exacerbating the NOx formation issue.

To date the solutions to lower NOx emissions to acceptable levels are expensive in terms of efficiency penalties or OPEX/CAPEX of end of pipe technologies as for example selective catalytic reduction (SCR) (Major and Powers, 1999). Considerable development has been made for the syngas fired gas turbine of conventional IGCC plants where hydrogen is the major fuel component and commercial plants are available. IGCC plants with pre-combustion CO_2 capture operate similarly to the plants without CO_2 capture, but with the inclusion of a water gas shift reactor and a CO_2 separation unit upstream the power island which is thus fired with high content hydrogen fuel (cf. Table 2). With or without CO_2 capture, the NOx formation problem in the diffusion type combustor is tackled by using large amounts of diluent in the high hydrogen content fuel. Nitrogen and steam are both potential diluent candidates because they are available at relatively low cost on site of IGCC plants. Steam/fuel ratio of unity was shown to half the NOx emissions from 800 ppm @ 15% O_2 dry (1.6 g/Nm^3) in Cocchi et al. (2008b) and Sigali et al. (2010). Although steam is demonstrated to be more effective than nitrogen (Wu et al., 2007), the latter is preferred firstly because steam affects significantly the heat transfer properties of the hot exhaust gas flow and reduce components life (Chiesa et al., 2005; Gazzani et al., 2014). Secondly, nitrogen is a readily available by-product of the air separation unit (ASU) present on site for producing O_2 for the gasifier.

Good emissions results have been proven in industrial cases with syngas and the use of diluents on diffusion type combustors as reported in several works (Todd and Battista, 2000; Wu et al., 2007; Gazzani et al., 2014). Although available at low costs, using nitrogen as diluent induces an expense of up to 20–30% of the total auxiliary power consumption required for its compression to slightly above cycle pressure. For comparison this share is even higher than that of the CO_2 compression power in the case of pre-combustion plant (Anantharaman et al., 2011). From a cost perspective the compressor unit is expensive and bulky Gazzani et al. (2014) showed that dilution used in combination with diffusion type combustors imposes an efficiency penalty of 1.5% points as compared to the reference combined cycle plant if the amount of nitrogen dilution is that required to reach a flame temperature similar to that of a natural gas flame. The penalty becomes 3.5% points in the case of steam dilution. The selected dilution degree and corresponding efficiency decrease is to be compromised with NOx emissions since these are exponentially proportional to combustion temperature (Ströhle et al., 2006; Todd and Battista, 2000).

The implementation of DLN combustors would avoid the inert dilution to lower NOx emissions. However, to counteract the aforementioned excessive flashback propensity, high injection velocity, and therefore, high pressure drop would be needed, which in turns has an efficiency cost as shown in Gazzani et al. (2014). Consequently, DLN burners have not been achieved to date for high hydrogen content fuels. Note that even if lean premixed combustion (i.e., low temperature) of hydrogen could be achieved through DLN burners, Therkelsen et al. (2009) measured NOx emissions that were still higher than in a methane flame at the same temperature. They attributed this effect to the higher propensity of the H_2–air chemical kinetic to produce NO through the low temperature NNH pathway (Bozzelli and Dean, 1995; Guo et al., 2005).

The present work suggests a gas turbine cycle concept that has a potential for low NOx emissions without the need of either fuel dilution or combustion technology breakthrough. By recirculating the exhaust gas to the gas turbine compressor inlet, the air entering the combustor is oxygen depleted, and inherently limits the combustion temperature and NOx formation. With this concept, the burner and combustor are simple and reliable (diffusion type) and would avoid the high cost and risks associated with the development of complex DLN burners and combustor arrangements for hydrogen rich fuels. The concept is already known within conventional natural gas combined cycles (NGCC) as Exhaust Gas Recirculation (EGR) (Li et al., 2011a,b, 2012), but for power cycles based on hydrogen fuels, it has to our knowledge, not been evaluated in the scientific literature, apart from a preliminary study by the authors (Ditaranto et al., 2014). The study aims at assessing the combustion properties and NOx emissions at various EGR rates to assess the technical feasibility of such concept in terms of combustion stability and emissions.

2. Description of the hydrogen fired gas turbine with EGR

2.1. Power cycle concept

The proposed core gas turbine cycle is depicted in Fig. 1. The turbine exhaust gas of a hydrogen fired gas turbine is composed of mostly nitrogen originating from the air, steam being the product of hydrogen combustion, excess oxygen and minor fractions of carbon dioxide. The basis of the concept is to adapt exhaust gas recirculation (EGR) to the cycle, where the EGR rate is defined as the ratio of the volume flow of recirculated exhaust gas to that of exhaust gas. By recirculating a fraction of the turbine exhaust gas back to the gas turbine compressor inlet, the gas flow through the compressor and entering the combustor has a reduced oxygen concentration. The NOx formed by the combustion of hydrogen in O_2 depleted atmosphere, is intrinsically limited by the reduced achievable adiabatic temperature. With a conventional fuel like natural gas or oil, the potential of such technique would rapidly be limited by flame stability (ElKady et al., 2009). However, the very reactive characteristics of hydrogen as fuel circumvent this shortcoming as it will be demonstrated in this study.

The moisture content of the turbine exhaust gas to be recirculated can be controlled through condensation before recycling into the inlet of the gas turbine. On the one hand steam has the positive effects of increasing the total mass flow and reducing the NOx formation. On the other hand high moisture concentration can lead to problems on the hot turbomachinery parts such as higher heat transfer to the turbine inlet blades (corrosion, thermal barrier coat-

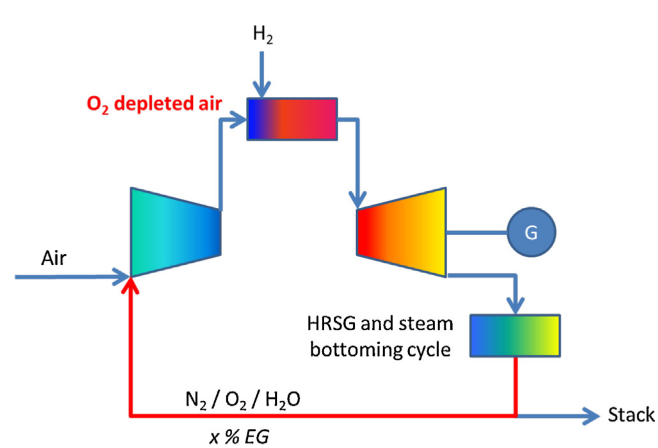

Fig. 1. Simplified layout of the hydrogen fired gas turbine with exhaust gas recirculation concept.