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

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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.

Keywords:

Exhaust gas recirculation (EGR), pre-combustion CO_2 capture, IGCC, Hydrogen gas turbine, NOx

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 [1] and gas turbine tests [2]. For example, Cocchi et al. [3] 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 [4]. 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 rates, preferential diffusion and higher flame temperatures leading to short auto-ignition times and high flame speed [5]. 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 [6, 7], 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) [8]. 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 Sigali et al. [9, 10]. Although steam is demonstrated to be more effective than nitrogen [11], the latter is preferred firstly because steam affects significantly the heat transfer properties of the hot exhaust gas flow and reduce components life [5, 12]. 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 [2, 11, 12]. Although available at low costs, using nitrogen as diluent induces an expense of up to 20% to 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 [13]. From a cost perspective the compressor unit is expensive and bulky. Gazzani et al. [12] showed that dilution used in combination with diffusion type combustors imposes an efficiency penalty of 1.5 percentage 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 percentage 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 [1, 2].

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. [12]. 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. [14] 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 [15, 16].

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) [17-19], 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 [20]. 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.

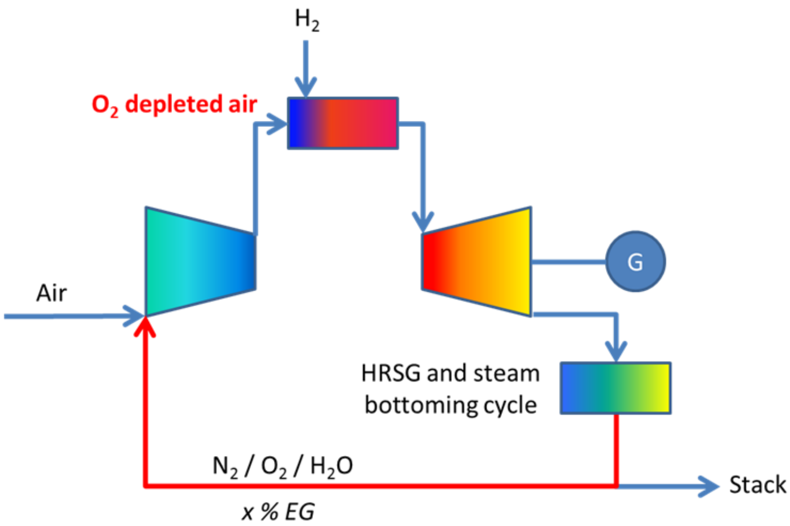

Figure 1: Simplified layout of the hydrogen fired gas turbine with exhaust gas recirculation concept.

2. Description of the hydrogen fired gas turbine with EGR

2.1. Power cycle concept

The proposed core gas turbine cycle is depicted in Figure 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 [21]. 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 coating degradation), and also on the compressor (corrosion, fouling). EGR in gas turbines is also the general principle used in semi-closed oxy-fuel gas turbine cycles where the goal is to replace all the air by the products of combustion of a pure oxygen fired combustor. Thus the working fluid becomes CO_2 which has very different physical properties than air, implying the need for a total re-design of the power cycle layout and components such as turbomachinery [22]. When EGR is applied to a hydrogen fired Brayton cycle, the working fluid is also affected to become richer in nitrogen and in the case of wet EGR, also richer in water vapour content. The effect on the physical properties of the working is shown for an extreme recirculation rate of 60% in Table 1, showing that these are nearly identical and very close to the air case in dry and wet EGR modes respectively. Indeed, close molecular weights and specific heats ratios imply similar mass flow and isentropic efficiency, hence unaltered thermodynamic performance for the gas turbine. The impact can therefore be expected to be less than in conventional natural gas fired gas turbine with EGR as described in Li et al. [17].

Table 1: Working fluid properties at selected EGR rate at 288 K compressor inlet temperature.

Case	MW (g/mol)	C_p/C_v (-)	Sound speed (m/s)	$T_{comp.\ exit}$* (K)
Air	28.86	1.401	340.9	689
60% dry EGR	28.83	1.400	341.0	688
60% wet EGR	26.55	1.384	353.2	671

** Polytropic efficiency=0.95, pressure ratio=18.1 bar as in [13].*

2.2. Combustion concept

In a conventional gas turbine combustor, part of the air is drawn into the primary flame zone to ensure flame stability. The remaining air is further split where a fraction is used for liner cooling purposes and another for dilution of the combustion products in order to reach the turbine inlet temperature and homogenise the temperature profile of the flow entering the turbine stage [23]. In modern DLN combustors, a higher part of the air is used in the primary zone in order to be premixed with the fuel such as to limit the maximum flame temperature. Most manufacturers have tackled the problems related to flashback and stability in this manner, and the technology is now commercial for hydrocarbon fuels. For the reasons explained previously, a different alternative to the DLN burners based on lean premix technology is necessary for hydrogen rich fuels due to its high reactivity.

In the present concept, the mixture of oxidizer and H_2 fuel is kept less reactive by depleting the oxygen in the air through recycling of the exhaust gas. Elkady et al. [21] in a NG fired gas turbine could operate a gas turbine combustor with up to 35% recycling of turbine exhaust gas, and an O_2 concentration of 17.8%. Ditaranto et al. [24] has shown in a laboratory scale swirl stabilized burner that combustion of methane could be sustained in a exhaust gas of a gas turbine at O_2 concentration levels as low as 15%. It is expected that this limit can be further reduced with hydrogen thanks to its higher reactivity.

Ideally a diffusion combustor would be used due to its design simplicity and low cost, and without inert gas dilution of the fuel for efficiency loss reasons as explained previously. The EGR concept has the potential for fulfilling both these requirements. Nevertheless, the reactivity of hydrogen, which limits the implementation of premixed burner technology, is no longer a barrier when the air is sufficiently oxygen depleted. Therefore the present concept based on EGR also enables the use of premixed burners with hydrogen combustion and push the potential for low NOx performance further down.

3. Methodology

The expected combustion characteristics in terms of stability and NOx emissions are evaluated through kinetic modelling of a premixed freely propagating flame using the chemical kinetic code LOGEsoft [25]. The combustion stability is estimated based on the comparison of the laminar flame speed of the H_2 rich fuel in EGR conditions against the value in a conventional known combustor configuration. The approach has been used in Sundkvist et al. [22] and this study uses the same combustor as reference. For predicting the NOx emissions the calculated concentrations from equilibrium chemical kinetics are compared to the value of that of a H_2 flame in air in the same pressure and temperature conditions. The absolute values obtained in a laminar premixed flame are surely different than what could be expected in a turbulent flame developing in an industrial combustor, but in this work the analysis is focused on the relative reduction obtained which is purely controlled by chemistry. This approach must be considered as a first order evaluation of stability and NOx emissions as it does not include the complexity of coupled turbulence – chemistry interaction, but it gives relevant trends and sets the limits of feasibility study of the power process concept. The results of this study further define the operational boundaries of the gas turbine engine and particularly that of the combustion unit.

The fuel and working fluid composition and temperature at the combustor inlet are calculated from the gas turbine case of the EBTF Guidelines IGCC cycle [13]. The fuel definition is given in Table 2. The exhaust gas of the gas turbine is recycled at various rates and the composition is re-calculated in each case. The combustor inlet temperature is calculated by assuming a 0.95 polytropic efficiency at the compressor stage and a constant pressure ratio of 18.1 bar. The reaction mechanism used in the premixed flame calculations is the full GRI-Mech 3.0 mechanism including the NOx subset, which in total contains 53 species and 325 reactions [26].

Table 2: Fuel composition (% vol.) [13].

H_2	CO	CO_2	N_2	Ar	H_2O
85,64%	2,66%	3,24%	7,27%	1,14%	0,05%

4. Results and discussion

4.1. Diffusion combustor mode

The first generation gas turbine combustors were fitted with safe and simple burner, so-called diffusion type, where the non-premixed fuel and air are injected directly into the primary combustion zone. The main duty of such a combustor was to ensure good ignition and stability of flame. This type of combustor was rapidly obsolete when emission limits on nitric oxides (NOx) became more and more stringent. In diffusion combustion, reactions develop at the air and fuel interface where reactants have mixed enough to reach flammability limits. As a result the flame sits preferentially at the near stoichiometric locations where the reaction rates are higher. This is also the location where the temperatures are closer to the maximum flame adiabatic temperature and therefore the location of highest NO formation as the thermal NO pathway is strongly temperature dependent [27]. In hydrogen flames, once NO is formed it cannot be reduced as there are no CH_i species that can activate the NO reburning mechanism. As a consequence, even if the global air to fuel ratio is large, NOx emissions from diffusion flame burners must be assessed by estimating the NOx formed in stoichiometric conditions. In this section, calculations in stoichiometric proportion of fuel and air are made in order to evaluate the potential of NO reduction by applying EGR to the hydrogen fired gas turbine.

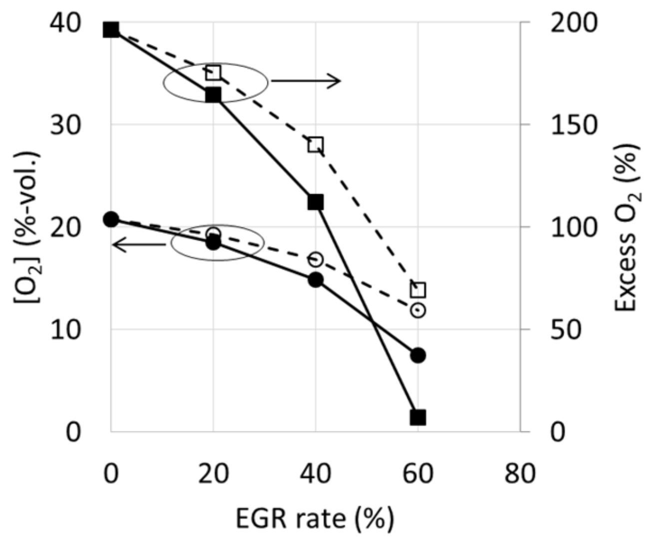

Figure 2: Oxygen concentration in the working fluid entering the combustor and corresponding excess oxygen over stoichiometric combustion value. Filled symbols: wet EGR; open symbols: dry EGR.

Recirculating exhaust gas depletes the combustion air of O_2 by dilution with H_2O and N_2 as shown in Figure 2. Oxygen concentration drops rapidly as the EGR rate increases and faster in wet than in dry mode. At some point the oxygen concentration is so low that an under-stoichiometric amount is reached as shown in Figure 2. The adiabatic combustion temperature in stoichiometric combustion shown in Figure 3 is the highest temperature that can be found in diffusion flames. At 60% EGR rates it steeply decreases from 2750 K down to 1580 K and 2020 K wet and dry respectively. As the thermal NOx pathway has a strong exponential dependency to temperature, the accompanying decrease in NOx formation as EGR increases shown in Figure 3 is very effective. Indeed, NOx concentrations are halved for an EGR rate of ca. 30% and 40% in wet and dry EGR modes respectively as compared to the case without EGR. These equilibrium calculations are more qualitative than quantitative as several parameters contributing to the NOx concentration such as residence time in the high temperature zone (hardware dependent), turbulence – chemistry interactions (burner design dependent), and radiative heat loss effects are not taken into account. Nevertheless these results are useful in predicting the trends in a worst case scenario and they indicate that a moderate rate of recirculation could achieve strong reduction in NOx without the expense of nitrogen dilution and compression as in the reference case [12, 13]. Cocchi et al. [9] measured a three-fold increase of NOx emissions when switching from natural gas to hydrogen fuel in a diffusion type gas turbine combustor. According to Figure 3 a 40% wet or 50% dry EGR rate would compensate equivalently such an increase in NOx emissions.

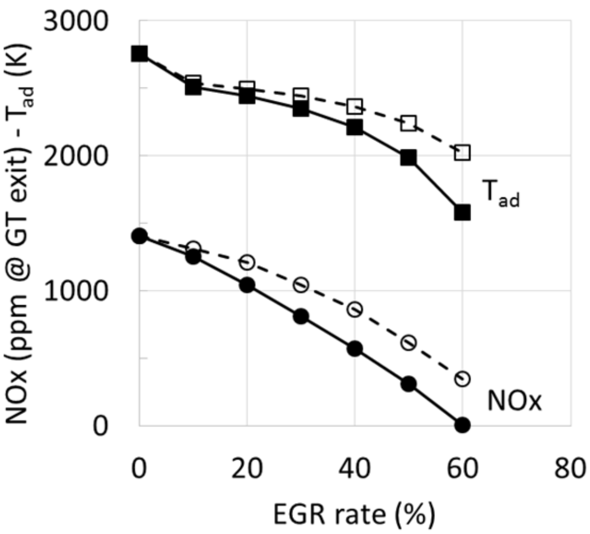

Figure 3: Calculated equilibrium NOx corrected at the GT exit and adiabatic temperature of stoichiometric combustion of the hydrogen rich fuel vs. EGR rate at gas turbine conditions. Filled symbols: wet EGR; open symbols: dry EGR.

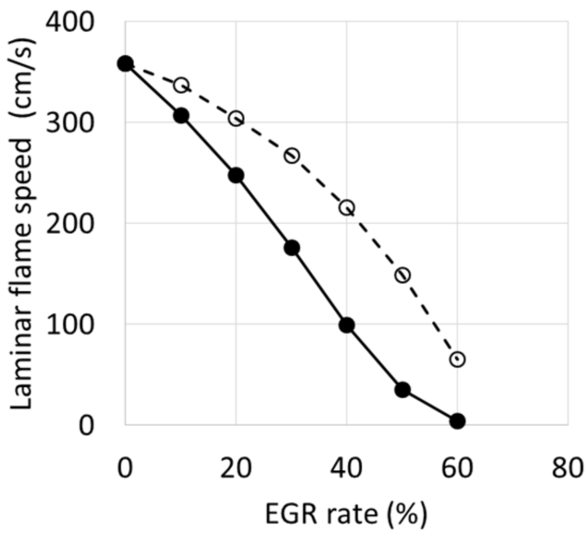

Figure 4: Laminar flame speed of stoichiometric combustion of the hydrogen rich fuel vs. EGR rate at gas turbine conditions. Filled symbols: wet EGR; open symbols: dry EGR.

Flame stability and NOx have been strongly related topics in clean combustor development in the last decades. The general strategy for lowering NOx production has been to tackle the high temperature regions of the flame by premixing air and fuel in large ratio. The further away from stoichiometry the premixing ratio is, the lower the flame temperature is, but unfortunately the weaker the combustion stability is too. Although flame stability in industrial burner is driven by a complex combination of aerodynamics and chemistry, laminar flame speed is a good first order indicator of flame stability. The laminar flame speed is a combustion property for a given mixture determined through kinetic chemistry. Figure 4 shows that at EGR rates of up to 50% and 60% for wet and dry EGR respectively, laminar flame speeds are close to 50 cm/s. As a reference, gas turbine combustor fired with natural gas have laminar flame speed values in the order of 20 cm/s, suggesting that stability should not be impaired by these high levels of EGR. This is due to the well documented positive effect of hydrogen as fuel on different configurations such as jet flames in co-flow [28], counter-flow flames [29], and swirl stabilized flames [30] to name but a few. The EGR rate limit in gas turbine with conventional fuels was identified by ElKady et al. [21] at around 35 % after which stability issues started to arise, but with hydrogen this limit is pushed further higher. In that concept the reactivity problem of hydrogen is then turned into a benefit by increasing the potential for higher EGR rates and stronger temperature decrease. The belief in the concept is further strengthened by the tests done in a full scale single burner in York et al. [31], where a premixed burner fuelled with 66% H_2 and 34% N_2 at 17 bar showed a reduction of NOx emissions with a 20% N_2 diluted air.

5.2. Premixed combustor mode

In conventional gas turbine combustors, part of the air is drawn into the primary flame zone (PZ) where most of the heat release occurs, while the remaining air is used for liner cooling purposes [23]. In modern gas turbines, more and more air is used in the PZ to fulfil the lean requirement of DLN burners. The air bypassing the PZ is introduced as dilution of the flame products to reach the maximum allowable temperature at the turbine stage. The degree of distribution between the primary and dilution air is design strategy, hence manufacturer dependent. By using a premixed flame configuration, we consider in this section the potential of NOx emissions reduction in the case where a perfect premixing is achieved in the PZ. As discussed previously, premixed burners are challenging if not impossible to achieve with hydrogen, and therefore require a certain degree of EGR to be applicable. Laminar flame speeds are presented together with NOx calculations in order to assess at which EGR levels premixing is achievable.

For the EGR gas turbine concept, a combustor strategy needs to be chosen to split the working fluid now composed of air and recycled exhaust gas. The conservative guideline used in this first approach is to maintain the PZ temperature and laminar flame speed close to those of a conventional combustor PZ. The reference combustor used has a PZ adiabatic temperature of 1780 K and a turbine inlet temperature (TIT) of 1583 K as in Sundkvist et al. [22]. The laminar flame speed at the reference combustor PZ conditions is in the range 16 – 20 cm/s. Results with working fluid distribution strategies from 45% to 100% in PZ are shown in Figure 5 to Figure 8. NOx emissions shown with different air distributions in the PZ are given at the gas turbine exit station. In other words, NOx concentration is calculated in the PZ conditions and then diluted with the bypassed working fluid. This approach is acceptable as the NO chemistry is little active at the lower temperature. NOx results in Figure 5 and Figure 6 are normalized by a reference NOx value calculated at stoichiometric conditions with no EGR, in order to compare with the diffusion flame case.

As expected, the more working fluid in the flame zone, the lower the NOx emissions due to leaner equivalence ratio. At 45% in PZ the conditions are close to stoichiometry, which means high temperature for low EGR rate cases. At this low distribution of working fluid in the PZ, EGR rate is limited by the amount of oxygen available in the PZ. At 40% wet EGR (Figure 5) the PZ is under-stoichiometric, explaining why NOx drops suddenly to nearly zero. Operating a combustor with a fuel rich primary zone is not impossible and can be seen as a relevant technology (a.k.a. Rich Quench Lean combustor), particularly with hydrogen rich fuels which produce stable combustion and do not exhibit eventual problems of unburned hydrocarbons and soot. The analysis of a detailed combustor layout for the EGR concept is however outside the scope of this study and we conservatively consider a PZ with 45% of working fluid as the lower limit of possible split ratio.

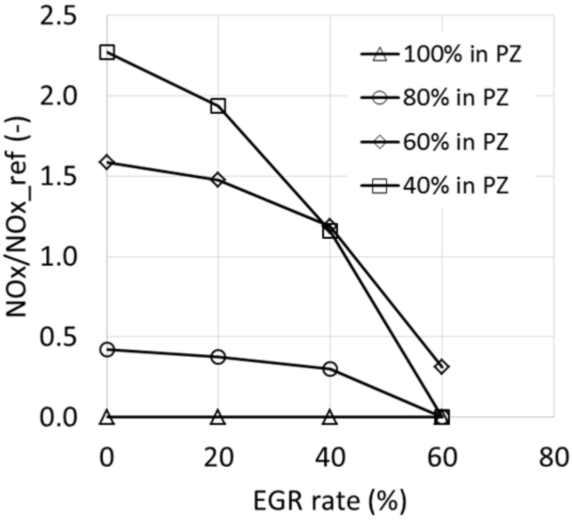

Figure 5: Calculated equilibrium NOx emissions from the gas turbine with dry EGR at different working fluid distribution ratios in the primary flame zone (PZ) of the combustor.

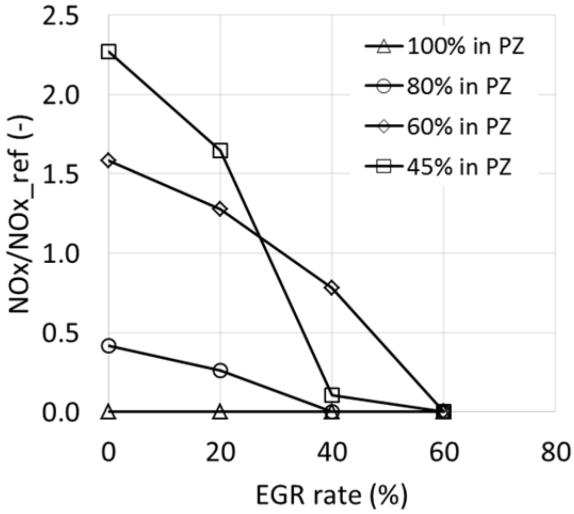

Figure 6: Calculated equilibrium NOx emissions from the gas turbine with wet EGR at different working fluid distribution ratios in the primary flame zone (PZ) of the combustor.

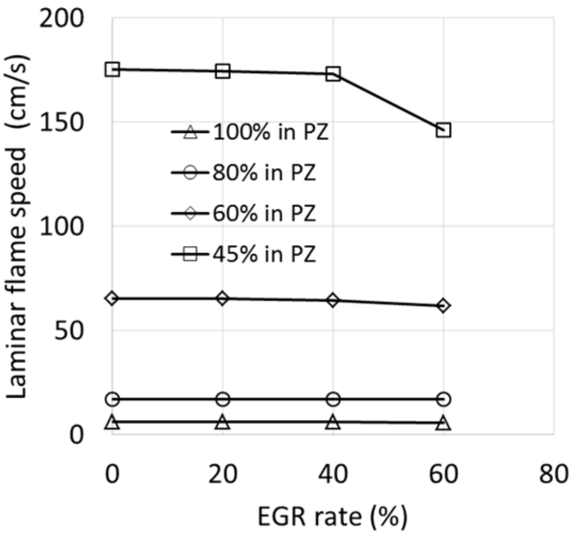

Figure 7: Laminar flame speed property in the primary flame zone (PZ) of the combustor with dry EGR at different working fluid distribution ratios.

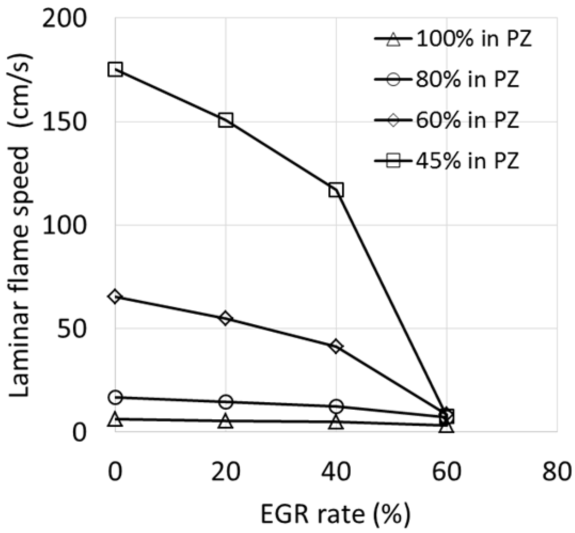

Figure 8: Laminar flame speed property in the primary flame zone (PZ) of the combustor with wet EGR at different working fluid distribution ratios.

An interesting finding is that the combustion temperature at constant working fluid distribution in PZ and varying dry EGR rate is almost constant, indicating that the NOx reduction observed with EGR is only achieved through a kinetic effect independent of temperature. This kinetic effect is controlled by the availability of oxygen which concentration decreases as EGR increases. The NOx reduction in the case of wet EGR seen in

Figure 6 is stronger than in dry EGR because of the presence of steam which has a double effect. First, there is a kinetic effect on the NO chemistry through changes in the pool of radicals induced by the increase in H_2O. Secondly the adiabatic temperature is reduced due to the higher heat capacity of steam as compared to the other species it replaces, namely N_2 and O_2. It can be observed from Figure 7 that for a given PZ split, the laminar flame speed for dry recycle has a very little dependency on the EGR rate. This singularity is also linked to the previous observation that the temperature remains constant as dry EGR rate varies.

Bearing in mind that the laminar flame speed of the reference combustor is in the range of 20 cm/s, the results in Figure 7 and Figure 8 indicate that working fluid up to 80 % in the PZ is possible, with corresponding low NOx potential. However, to achieve premixing before combustion the laminar flame speed at stoichiometric conditions must be low enough. The values given in Figure 4 indicate that high enough EGR rates would be necessary to avoid potential flashback that would render impossible DLN technologies.

5.3. Practical application

Figure 9 is an attempt to map the boundaries of applicability of the DLN and diffusion combustor technologies as a function of EGR rate in the dry and wet modes. The charts show that achievable premixed technology in dry mode is only possible within a restricted working fluid distribution, and acceptable NOx emissions require an EGR rate of approximately 50 % depending on PZ distribution. For the wet case, there is a larger possible premixed flame domain, but limited to higher EGR rates if low NOx emissions are to be achieved. The diffusion combustor technology with ensured low NOx has a much wider range of applicability as long as EGR rates are above ca. 50 %. We recognize that these limits are quite crude because NOx is calculated on the basis of equilibrium calculations and the stability is assessed through a simplified manner. Nevertheless they indicate the feasibility of the concept and the design difference that can be expected with regards to existing technologies where typically more than 80% of the air is drawn into the primary zone of current DLN combustors.

From a first order combustion assessment, the concept seems promising and issues related to the power plant integration must be evaluated, such as efficiency gain or loss, optimization of the plant arrangement and the impact of parameters like the recycle rate. Indeed, the application of the EGR principle will affect the bottoming cycle which is very sensitive to the turbine exhaust gas temperature and mass flow. Proper integration is therefore necessary and there are different options that are conceivable. For example, to reduce the recirculation rate and the cooling demand in the condenser, the available nitrogen which comes as a free stream during the oxygen separation in the ASU, can be injected in the fresh air entering the compressor and thus reduce the amount of recirculation rate.

The study presented here is based on a pre-combustion CO_2 capture case with a fuel that has a 85 % vol concentration of hydrogen (cf. Table 2), however the concept is applicable to a conventional IGGC plant without capture. A syngas fuel with a lower H_2 concentration, but higher CO concentration has similar challenges since the combustion temperature of CO and H_2 are very close.

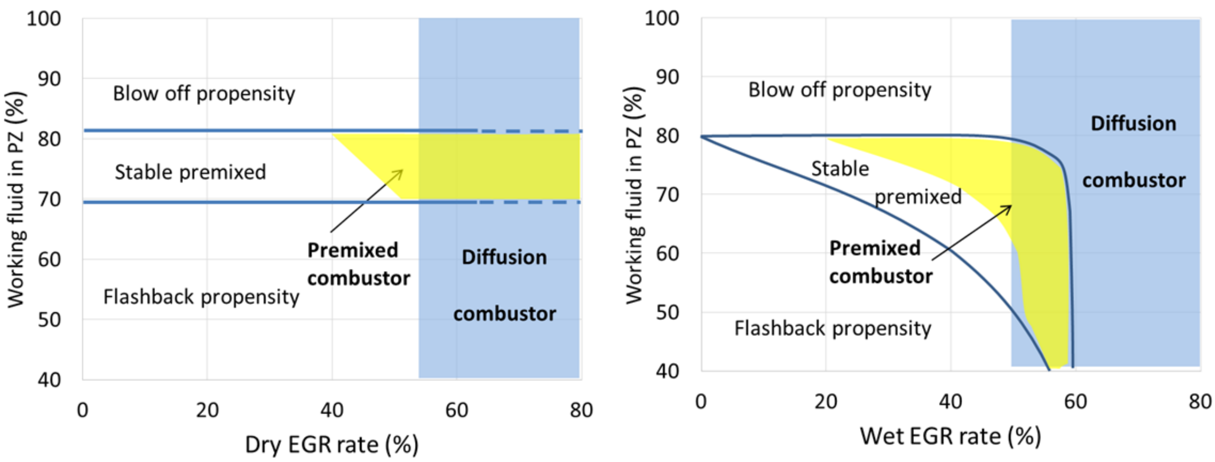

Figure 9: Selection of combustor technologies for the wet (LHS) and dry (RHS) EGR concept for low NOx emissions hydrogen fired gas turbine. Bold lines represent the limits of flame stability in premix flame mode; the shaded yellow area represents the operation island where premix mode is achievable and within low NOx limits; the shaded blue area represents the diffusion mode within low NOx limits.

5. Conclusions

A novel gas turbine cycle concept for power plant with pre-combustion CO_2 capture or IGCC is presented. Large inert gas dilution of the hydrogen rich fuel is commonly used to achieve low NOx emissions due to the high temperature combustion properties of hydrogen. The proposed gas turbine arrangement is set up to avoid the efficiency penalty associated with the dilution by applying high Exhaust Gas Recirculation (EGR) rate to generate an oxygen depleted working fluid. In this study, a first order assessment of the combustion characteristics in such a gas turbine condition is made and showed that with an oxygen depleted oxidizer, the high reactivity of hydrogen fuels is turned into a benefit to potentially achieve low NOx emissions. The conclusions on the combustion behaviour in such a cycle are as follows:

1. At high EGR rates the working fluid is so oxygen depleted that stoichiometric flame temperature are maintained low enough to avoid high NOx formation.
2. Flame stability can be maintained at high EGR rates because laminar flame speeds are high enough thanks to the high reactivity of hydrogen.
3. Increasing EGR rate in dry mode reduces NOx formation only through the kinetic effect of lower O_2 availability.
4. Increasing EGR rate in wet mode reduces NOx formation stronger than in dry mode because a thermal effect driven by increased heat capacity adds to the kinetic effect.
5. Diffusion combustors could be used, but at high enough EGR rates (i.e. very O_2 depleted working fluid) the use of lean premixed burners becomes also feasible thanks to the reduced reactivity of hydrogen.
6. Dry EGR is possibly the most efficient way of abating NOx because of the good overlap between stable operating flame conditions and low NOx formation regions.

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