Humidification Towards Flashback Prevention in a Classical Micro Gas Turbine: Thermodynamic Performance Assessment

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Abstract. Combustion air humidification has proven to be effective to stabilize hydrogen combustion and to avoid flashback apparition in a typical micro Gas Turbine (mGT). However, both the fuel alteration and combustion air dilution will impact the cycle performance. A complete characterization of this thermodynamic impact is essential to ensure that the mGTs become cleaner, and fully flexible to fit with the expectation of future small-scale decentralized power production. Therefore, the objective of this work is twofold: the determination of the necessary dilution for combustion stabilization, depending on the type of fuel, as well as the impact assessment on the cycle performance. In this framework, a hybrid model of the Turbec T100 mGT combustor, combining a 0D Chemical Reactor Network and 1D Laminar flame calculations, is used to first assess the flashback limits. The laminar flame speed is evaluated to predetermine the necessary minimal water dilution of the combustion air to avoid flashback for several CH_4/H_2 blends. Second, a thermodynamic analysis is performed to assess the impact of the flame stabilization measures on the cycle performance of the mGT using Aspen Plus. The 0D/1D simulation results show that the combustor of the Turbec T100 can operate with fuels containing up to 100% hydrogen. However, the thermodynamic analysis shows that the water dilution leads to a decreased electrical performance. Future work consists in the iterative coupling of both 0D/1D and the Aspen model to correctly predict the flashback limits, considering the altering operating conditions. To conclude, with this work, we provide a framework for future mGT operations with alternative fuels.

1 Introduction

Recent years have seen a significant increase in the contribution of renewable energy to electricity production at the expense of traditional, combustion-based thermal power production, to answer the urgent need for carbon emission reduction. Nevertheless, the unpredictable nature of renewable energy sources, like wind and solar, together with the large fluctuations in their production, put some severe constraints on the reliability and stability of the electricity grid. Moreover, large-scale battery storage, remaining expensive, does not offer a solution for medium- to long-term (seasonal) energy storage. Given these issues, there

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is nowadays a strong trend towards storing the excess renewable electricity using Power-to-Gas [1], i.e. production of hydrogen from excess renewable electricity using electrolysis, so-called green hydrogen.

The use of green hydrogen, produced using electrolysis to store excess renewable electricity, allows for combustion-based technologies to keep playing a key role in the future of power generation. Especially in a decentralized production with cogeneration, micro Gas Turbine (mGT) technologies offer great advantages related to their high adaptability and flexibility, in terms of operation and fuel. Combining the clean hydrogen production from renewable energies using Power-to-Fuel with carbon-clean combustion in the mGT facilitates the implementation of renewable energies for the energy transition [2]. However, hydrogen (or hydrogen-enriched methane/air) combustion is well known to lead to flame and combustion instabilities. The high temperatures and reaction rates reached in the combustor can potentially lead to flashback, causing thus major and irreversible damage to the facility.

Several approaches have been investigated and can be found in the literature to ensure stable and safe hydrogen combustion. Modifying the geometry and adapting the combustor layout is one of the most commonly achieved solutions. Although the proposed and studied layouts show complete and stable combustion at 100% H_2 input, they require a complete combustor redesign. These combustors are therefore not always suitable to burn CH_4 or other fuels, limiting the fuel flexibility of the mGT [3]. An alternative solution to avoid any redesign of the combustor stands in using diluted conditions to slow down the reaction. Combustion air humidification (steam or water addition) is another route that has proven effective to reduce the combustion temperatures and reaction rates, avoiding thus flashback apparition [4, 5]. Although this solution allows processing with only one combustor, a modification in the global cycle is needed, such as the implementation of a saturation tower or a steam boiler to inject water (or steam) into the cycle. Additionally, knowledge of the hydrogen limit in hydrogen-enriched methane combustion in mGTs, still leading to stable and complete combustion without requiring any redesign, is essential and allows future mGT operators to manage safely the combustion of different fuel mixes, without requiring an expensive combustor redesign.

Aiming at stabilizing hydrogen combustion in mGTs without any redesign of the combustor, this work presents thus the determination of the necessary dilution for combustion stabilization, depending on the type of fuel, as well as the impact assessment on the cycle performance. In this framework, a hybrid model of the Turbec T100 mGT combustor, combining a 0D Chemical Reactor Network and 1D Laminar flame calculations, is used to first assess the flashback limits. The laminar flame speed is evaluated to predetermine the necessary minimal water dilution of the combustion air to avoid flashback for several CH4/H2 blends. Second, a thermodynamic analysis is performed to assess the impact of the steam dilution on the cycle performance of the mGT using Aspen Plus.

2 Methodology

In this Methodology section, we will first present the 0D/1D model of the combustor, allowing to predetermine the necessary dilatation reduction to achieve stable combustion when using increased hydrogen fractions. Second, the used Aspen plus model, allowing to assess the impact of these measures on the cycle performance, is presented.

2.1 0D/1D combustor modelling

The mGT considered for the simulations is the Turbec T100 mGT. At nominal conditions, this mGT produces a net electrical power output of 100 kW_e while the combustor inlet conditions are a fuel consumption of 333 kW_{th} and an air mass flow rate coming from the compressor of 742 g/s. The T100 combustor features a can swirl burner (counter-current flow) where the combustion air is entering between the outer casing and the inner walls of the combustor. The air reaches then the dilution holes, the pilot, and the main injectors by passing on the external surface of the inner walls. The layout characteristics of this combustor are (**Figure 1**): a pilot flame exploiting a diffusion flame, fed by 12 air injectors and 6 fuel injectors; premixed combustion as main flame using two rows of swirler (a first one to premix fuel and air, and ending with 30 swirled injectors); and 9 dilution holes to cool down the exhaust gases to avoid any damages at the turbine inlet.

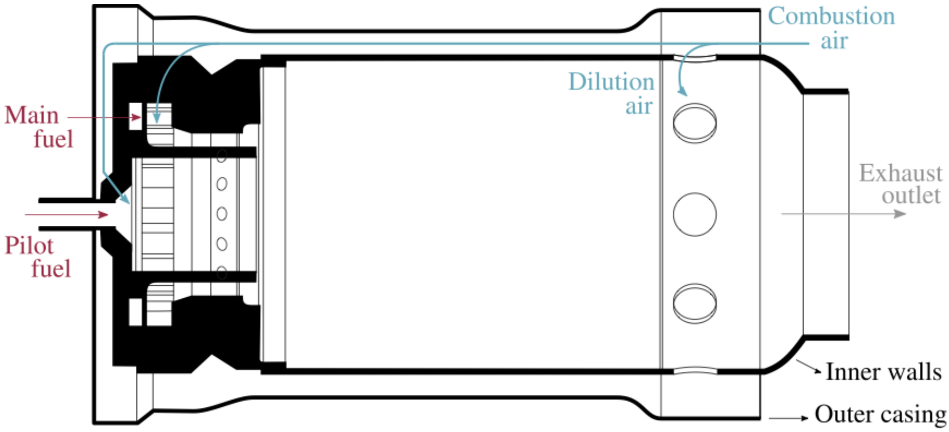

Figure 1. Cross section of the Turbec T100 combustion chamber.

Computations (both 0D CRN and 1D Flame) are carried out using the CANTERA software with the detailed GRIMech 3.0 (GRI 3.0) mechanisms (53 species and 325 reactions). Cantera allows simulating Continuously Stirred Tank Reactor (CSTR), also often referred to as Perfectly Stirred Reactor (PSR), by solving the mass, species, and energy conservation equations. As shown in **Figure 2**, a network of CSTR is built to emulate the behaviour of the T100 combustor. The main parts of the combustor are simulated using connected Reservoirs and CSTR. The Reservoirs are working as tanks at the defined operating conditions for the inlets of oxidizer and fuel, and for the exhaust. The CSTRs are used to simulate the pilot flame, the premixing zone of the main injectors (premix of the fuel and the oxidizer), the main flame (to consider the conjugated effect of the pilot flow with the main flame), and the dilution zone (mixing of the hot products with the fresh air passing through the dilution holes). Once the steady state of the 0D CRN simulation is reached, the state of the flow in the premix area is used to perform the 1D Flame calculation.

Several solutions exist to perform humidification. In this work, we consider adding the water before the combustion chamber at 4 bars and 450K, so after the recuperator which preheats the air coming from the compressor. As shown in **Figure 2** (blue block), a reactor is then needed to mix water with air at 865K, since this mixing will decrease the global oxidizer temperature. Hence, using a reactor upstream of the CRN of the T100 combustor allows considering this temperature drop for the 1D flame calculation. A water-to-air mass ratio Ω is defined as the ratio between the mass flow rate of added water to the oxidizer level of water dilution, and the total oxidizer mass flow rate (air+water).

Finally, it is worth noting that this tool, initially developed for the identification of the stability limits of humidified cycles fuelled with methane, has successfully been experimentally validated [6]. Although some discrepancies were observed for the CO emissions, finding their origin in the use of the PSRs, the tool allows correct prediction of temperatures, flame speeds and hence stability limits.

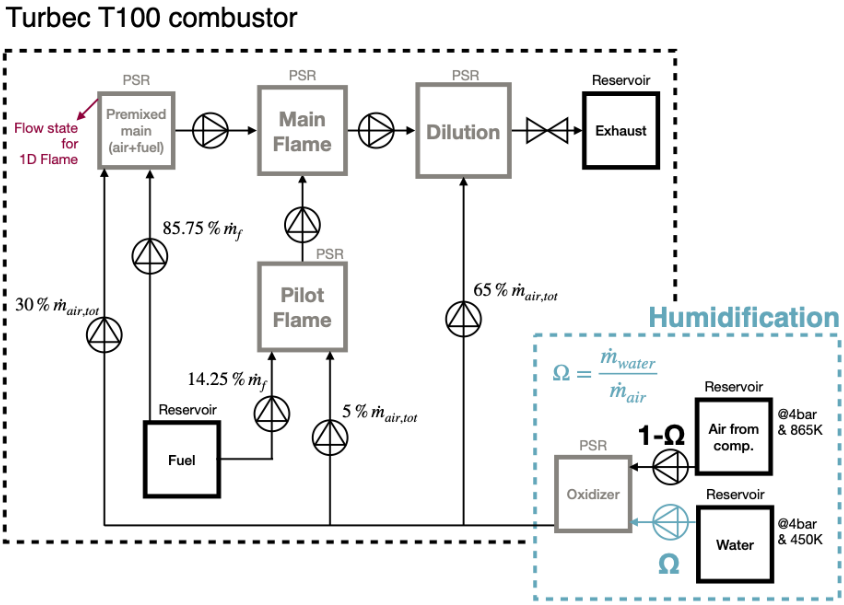

Figure 2. Chemical Reactor Network layout developed to determine the necessary level of combustion air temperature reduction/steam dilution towards hydrogen combustion stabilization.

2.2 Aspen Plus Cycle modelling

To stabilize the H_2 combustion in the mGT combustion chamber, the 2 considered strategies, being inlet air temperature reduction and steam dilution, should be implemented in the cycle of the studied mGT, being the Turbec T100. To be able to adjust the combustor inlet air temperature, a recuperator bypass, bypassing part of the compressed air over the recuperator and by doing so, reducing the heat recovery from the flue gas, is assumed. In this particular case, the recuperator bypass is assumed on the cold side, however, previous simulations of the authors showed that recuperator bypass on the hot side results in similar performance [7] and hence, the most practical suitable solution was opted for. For the steam dilution, although, from a cycle point of view, injection before the recuperator is favourable for enhanced waste heat recovery [8], to be as close as possible to the results of the 0D/1D simulations, injection in the recuperator cold side outlet (thus directly in the combustion air) is foreseen.

Simulations of the impact of these combustion stabilization techniques on the cycle performance were performed in Aspen Plus, starting from previously developed models of recuperator bypass [7] and steam injection [9]. For the turbomachinery modelling, performance maps were used for the compressor, while the turbine was assumed as choked (choking condition determined based on the turbine maps). This strategy was used prior by the authors with success [9]. For the recuperator, a specific heat exchanger model, exploiting a power law for correction of the heat transfer coefficient based on the altering flow rates (mainly for the temperature reduction strategies) was used. The combustor was modelled as a Gibbs Free Energy reactor, assuming a constant heat loss of 25 kW_{th}, complete combustion and 5% pressure loss. Finally, 99% mechanical and 96% of generator and power electronics efficiency.

The Turbec T100 typically operates at constant TIT (by controlling and keeping TOT constant) and power output, by altering the fuel flow rate and the rotation speed. In these specific Aspen simulations, constant thermal power input (fixed fuel mass flow rate) and constant rotational speed was considered. This was done to remain as close as possible to the conditions of the 0D/1D modelling, where constant combustor air mass flow rate and constant thermal power input were assumed. Indeed, operation at constant air mass flow rate cannot be achieved with the actual control system. Hence, constant rotational speed operation was selected.

3 Results

In this results section, first of the 0D/1D flame calculations are presented, followed by the corresponding cycle performance assessment using the same inlet let conditions of this 0D/1D modelling.

3.1 0D/1D stabilization predictions

Figure 3 presents a quantitative analysis of the laminar flame speed evolution for specific values of H_2/CH_4 blends, 25/75, 50/50, 75/25, and 100/0%$_{vol}$, when reducing the inlet temperature T_{in} and when performing humidification (through steam injection just before the combustor). The T_{in} is the mixing temperature between the fuel and the oxidizer in the premixing zone of the main injector. In normal conditions (*Ref case*), the temperature of the air coming from the compressor and the recuperator is 865K, while the premix temperature is 830K (in adiabatic conditions). The y-axis is the predicted dimensionless laminar flame speed S_l^0 divided by the laminar flame speed of the *Ref case* (100% CH_4). The full black line represents a flame speed ratio of 1, meaning that the laminar flame speed below this limit is lower than the one of a pure methane combustion case. methane combustion case.

As first observation, burning up to 100% of hydrogen in the Turbec T100 combustor seems possible for both proposed solutions, i.e., the inlet temperature of the oxidizer decreases down to 633K or requires a Ω ratio of at least 11.15%. The incoming oxidizer and fuel temperatures majorly impact the flame speed. **Figure 3** shows the minimum necessary inlet temperature reduction or quantity of water to bring the flame velocity back to the reference level. To reach the same level of velocity as the reference case, H_2/CH_4 blends of 25/75, 50/50, 75/25, and 100/0 require respectively a premix inlet temperature of 829K, 790K, 732K, and 633K, or a Ω ratio of 1.6, 3.5, 6.3 and 11.15%.

3.2 Impact on cycle performance

Applying the combustion stabilization techniques leads to a significant performance reduction (**Table 1**). Indeed, bypassing part of the combustion air over the recuperator, and while doing so reducing combustor inlet air temperature, negatively impacts the performance. Since the thermal input in the cycle was kept constant, a lower combustor inlet air temperature will lead to a lower TIT and thus reduced turbine power, negatively impacting the produced electrical power. The TIT dropped down from 930°C to 688°C for the increasing hydrogen fraction (**Table 1**). Especially for the 75/25 and 100/0 case, the TIT becomes unacceptably low, leading to significant efficiency reductions down to 17.5%.

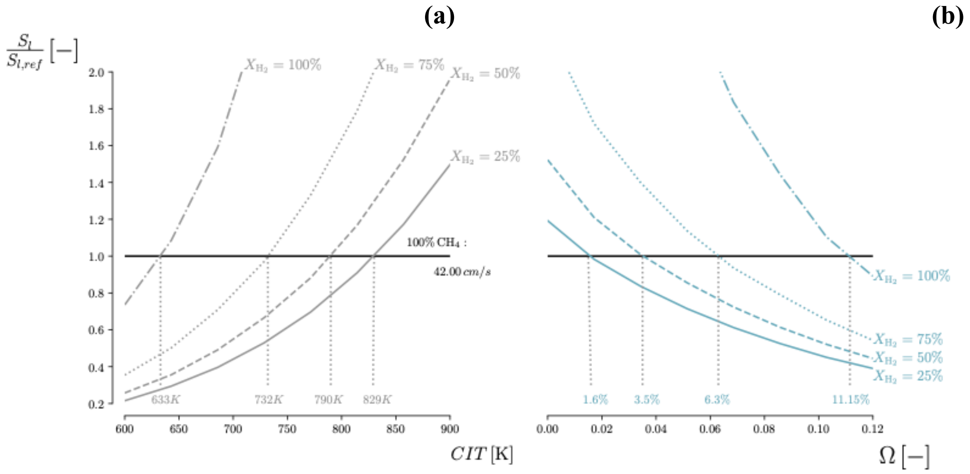

Figure 3. 0D/1D calculations allow to assess the minimal temperature reduction (a) and steam fraction (b) to stabilize the hydrogen combustion.

Finally, to obtain the reported combustor inlet temperature from **Figure 3**, a bypass ratio ranging from 5% up to 37% was required.

Similarly, as reported before [8], the injection of steam in the combustion chamber also leads to reduced cycle performance, although lower reductions are observed compared to the temperature control. A reason for this reduced performance can be found in the steam addition: due to the introduction of steam in the combustor, again the TIT is reduced as a result of the increase total mass flow as well as the heat capacity of the working fluid in combination with the constant thermal power that is imposed. Hence lower turbine power will be produced. This reduction is however limited since more mass flow rate is available due to the steam addition. Indeed, this effect can clearly be seen in **Table 1** when comparing the produced electric power between the temperature control strategy and the steam dilution strategy. However, it is important to note that in the calculation of the efficiency in this case, the energy needed to produce the steam is not considered (it is expected that the steam will be auto-raised in a heat recovery steam generator using the energy in the flue gases).

Table 1. Both proposed combustion stabilization techniques lead to a reduced performance of the mGT.

	Temperature Control					**Steam Dilution**				
H_2/CH_4	**P_{el}**	**η_{el}**	**m_{air}**	**TIT**	**TOT**	**P_{el}**	**η_{el}**	**m_{air}**	**TIT**	**TOT**
0/100	100.0	29.4%	0.742	930°C	645°C	100.0	29.4%	0.742	930°C	645°C
25/75	94.8	27.8%	0.752	896°C	618°C	97.9	28.7%	0.756	887°C	612°C
50/50	87.9	25.8%	0.764	855°C	585°C	94.9	27.8%	0.773	836°C	572°C
75/25	75.9	22.2%	0.784	784°C	530°C	91.2	26.7%	0.800	766°C	519°C
100/0	59.3	17.5%	0.813	688°C	445°C	86.6	25.5%	0.846	662°C	438°C

Finally, it is important to highlight that in both cases the total air mass flow rate in the combustor does not remain constant but is increasing due to the constant rotational speed control. This higher air mass flow rate leads to a reduction of the global equivalence ratio in the combustion chamber (thermal power was kept constant) and in the steam dilution case also to an additional reduced temperature of the combustion air entering the combustor due to the limited exchange surface of the recuperator. Since operation at lower equivalence ratio and temperature lead to reduced flame speed, it is expected that less temperature reduction or steam dilution is required to keep the flame speed constant and hence the impact on the cycle performance will be reduced. This however requires the coupling and iteration of both the 0D/1D model and the aspen cycle model, which was outside the scope of this paper, but will be considered in future work.

4 Conclusion

In this paper, the impact of two specific strategies for hydrogen combustion stabilization in a typical mGT, being combustor inlet temperature reduction and steam dilution, on the cycle performance was assessed. 0D/1D calculations allowed to assess the needed level of combustor inlet temperature reduction (reduction from 588°C to 359°C for 100% hydrogen) and minimal steam dilution needed (up to 11.15% of steam injection for 100% hydrogen firing) to bring the flame speed back to the reference level. The temperature reduction strategy was however shown to have the largest negative impact on the performance, while steam dilution allows to limit the negative impact, mainly due to the additional mass going through the turbine. Future works involve the coupling of both 0D/1D model with the cycle model, allowing to iteratively find the minimal temperature reduction or steam dilution, considering the altering operating conditions, resulting from the changing compressor operating point.

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