OPTIMIZATION OF INTERCOOLED REGENERATIVE REHEAT GAS TURBINE SYSTEM FOR MULTI-FUEL COMBUSTION

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Abstract

The simultaneous adoption of intercooling, regeneration and reheating allows to obtain very good results in increasing the efficiency of a gas turbine cycle. In particular, the reheating technique requires correct design to ensure efficient combustion conditions. The paper reports an analysis of reheating process for a small power gas turbine aimed at optimizing the combustion conditions in the reheater. Different configurations with different degrees of bypass were analyzed, by focusing the attention on the chemical kinetics. The aim was to optimize temperatures and oxygen concentrations at the reheater according to the specific fuel to be used.

The analysis was conducted with reference to methane, which is currently the most used fuel in land-based applications. In a broader vision and in the perspective of using alternative fuels, the adopted methodology is particularly useful for fuels which require particular conditions to stabilize the combustion process, such as ammonia.

Introduction

One of the most important challenges of this century for humanity is undoubtedly that of satisfying a growing energy demand. However, this will have to be done by simultaneously reducing the use of fossil fuels and therefore the production of CO2, to mitigate climate change [1]. Along this road, the technological perspective focuses on increasing the use of renewable sources and alternative fuels on the one hand, and on the other that of increasing the efficiency of energy production systems [2].

Regarding to gas turbines, the increase in efficiency can be achieved using one or suitable combination of some technological solutions as intercooling, reheating and regeneration. Unlike large-scale plants, usually combined with steam plants, in medium and small power gas turbines, all three of these techniques may coexist [3]. The technological evolution of plants with gas turbines has primarily concerned the increase in efficiency thanks to the increase in the maximum temperature TIT (turbine inlet temperature); all this has required the development of increasingly sophisticated refrigeration techniques for the blades and combustion techniques to mitigate the production of thermal NOx [4]. The coexistence of the three techniques already mentioned, allows for significant increases in efficiency without the need for too high TIT values. Among the applications that have recently seen the greatest development of these techniques there is certainly the automotive sector, using micro gas turbines coupled to electric generators for recharging the batteries [5]. That's the case of range extender applications (RE) and several studies are in progress on the optimization of the Brayton cycle of such turbo gensets [6].

The proposed study concerns a similar application, a plant with a low-power, intercooled, reheated and regenerative gas turbine. In this specific case the attention was paid to the reheating section, analyzing different configurations with different degrees of by-pass of the gases coming from the first expander. The study of the chemical kinetics of the combustion process in the second combustor was carried out for methane, in the first analysis; however, the methodology adopted can also be applied to the study of alternative fuels. Ammonia, for example, which presents significant combustion problems due to its low reactivity, could be burnt in the reheater, by creating the right condition in terms of reactant temperature and oxygen concentration and eventually methane blending [7].

Methodology

The reported study aims at identifying the suitable solutions to optimize a Brayton external combustion gas-turbine system for extended range electric vehicles. In particular, an intercooled-reheat Brayton cycle, equipped with a regenerator recovering heat on the outlet of the second turbine to preheat the incoming air stream fed to the first combustion system (reported in Figure 1 along with the respective operative characteristics) was considered, with specific focus on the combustion system optimization.

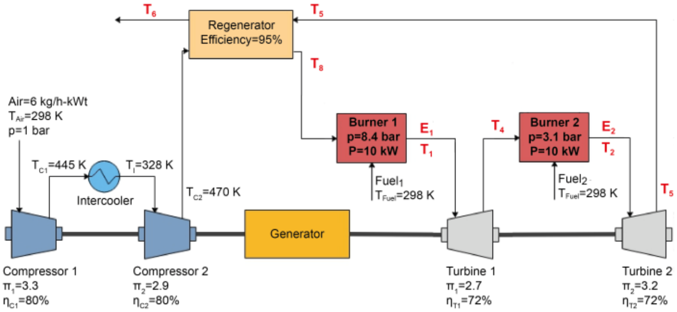

Figure 1. *Brayton system configuration considered in the analysis.*

In this respect, a parametric numerical analysis was carried out in order to identify the most effective configuration and the optimal operative conditions ensuring stable combustion, acceptable pollutant emissions (namely CO and NO_x) and suitable operational temperatures (red in Figure 1), while meeting the operative requirements reported in Table 1. Specifically, fundamental prerequisites driving the performed optimization analysis were the turbine inlet temperature limit, fixed at 1373 K to be compatible with specific alloys of turbine elements for medium temperature applications, and the air mass flow rate (6 kg/h-kWt), essential to ensure a global efficiency about 43%.

Table 1. *Operative requirements and burner specifics.*

Turbine inlet temperature limit, K	*1373*
Air mass flow rate, kg/h-kWt	*6*
Efficiency	*> 43%*
Maximum cycle pressure, bar	*8.76*
T_{in} *Air Burner 1* (T_8), *K*	*1023*
Fuel	CH_4
Total thermal power, kW	*20*
T_{in} *Fuel* (T_0), *K*	*298*
Burners Volume, cm^3	*2000*
Heat Transfer Coefficient, cal/cm^2*-K-s*	$1.8{\cdot}10^{-3}$

To meet the identified requirements, a cyclonic-flow combustion chamber, extensively described in literature [7–9] and operating under MILD combustion conditions [10], was considered as combustion unit. In this respect, the intense internal recirculation of combustion products due to the burner design and feeding mode was already demonstrated to ensure a wide range of combustion stability, flexibility to the fuel type, reduced pollutants formation and moderate operative temperatures (<1500 K) [7,9]. Both the burners reported in Figure 1 were modelled as a Perfectly Stirred Reactors (PSR), provided by CHEMKIN PRO [11] package, with a volume of 2000 cm^3 and a nominal thermal power P=10 kW each, using methane as fuel.

Simulations were carried out in non-adiabatic conditions, by fixing the heat transfer coefficient equal to $1.8{\cdot}10^{-3}$ cal/cm^2-K-s, as estimated in a previous work [12], and an exchange area of 1200 cm^2. Combustion stability and pollutant formation were investigated by the C_1-C_3 detailed kinetic mechanism [13].

Results

Preliminary analyses were performed in order to evaluate the characteristic ignition delay times τ_{ig} (ΔT=10 K with respect to the non-reactive conditions) and oxidation times τ_{ox} (time to achieve the final system temperature) of a reactant mixture evolving under the conditions reported in Table 1. Specifically, the air mass flow rate was set equal to 120 kg/h, as required for a thermal power equal to 20 kW, at 1023 K, while the operative pressure was systematically varied in the range 2 bar<p<10 bar. Obtained result, not reported for the sake of brevity, highlighted $0.1s<\tau_{ig}<0.17s$ and $0.3s<\tau_{ox}<1s$ for all the investigated pressures levels, while the nominal residence time always keeps lower than 0.3 seconds. In this respect, to ensure the reactants ignition and their complete and stable oxidation, it is essential to investigate suitable configurations able to achieve longer residence times. Among the possible effective solutions (i.e. larger reactor volumes, reduced thermal power etc.) the partition of the total air flow rate fed to the first reactor was investigated, following the flowsheet reported in Figure 2. The influence of the air bypass ratio (R_1=Air_2/Air) was systematically investigated, in terms of combustion stability, pollutants emissions and operative temperature levels of the Bryton system. In particular, the air bypass stream is supposed to be fed around the burner case, to continuously heat exchange, and then mixed with the combustion product exit from the burner. The investigated bypass ratio levels were fixed to entail equivalence ratio values of the Burner 1 between 0.1-1.

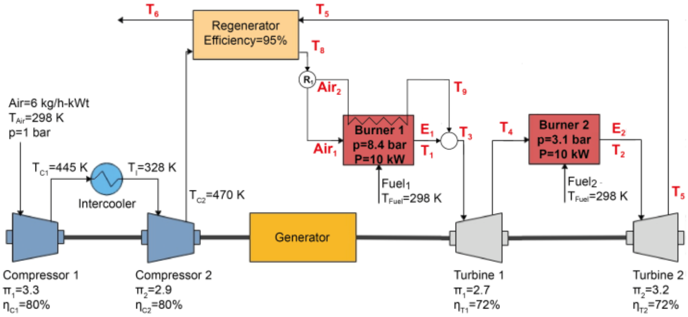

Figure 2. *Scheme1: System configuration with Air bypass to Burner 1.*

Main results are reported in Figure 3, in terms of operative temperatures and pollutant emissions. With reference to Figure 3a, by increasing R_1 the burner operative temperature increases, as expected, due to the resulting equivalence ratio increase with R_1, that in turn ensures the oxidation process stabilization. On the other hand, inlet turbine temperatures smoothly increase by increasing R_1. They always keep lower than the allowable limit, not exceeding 1260 K and 1150 K, respectively.

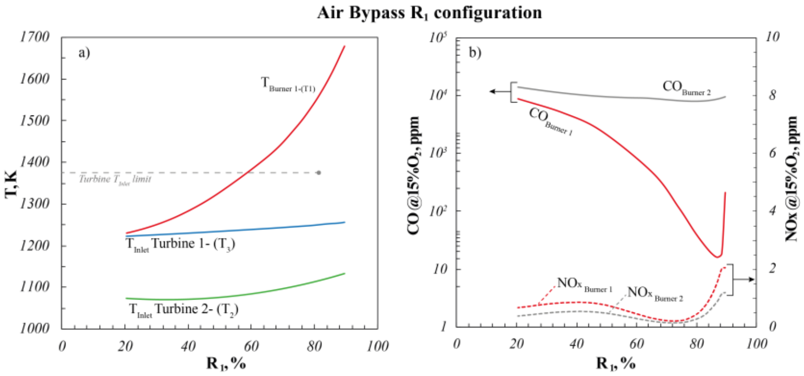

Figure 3. *Scheme 1: Operative T (a), CO and NO_x emissions (b) vs %R_1.*

In Figure 3b NO_x and CO emissions, normalized at 15% of O_2, and characterizing both the burners are reported as a function of R_1. Specifically, NO_x emissions always stay below 3 ppm. Instead, CO emissions show different behavior depending on the considered burner. In particular, a non-monotonic trend characterizes CO levels of Burner 1, with a minimum of about 16 ppm located around R_1=87% and increasing CO emissions for both higher and lower R_1. For R_1<87% the decreasing residence times within the reactor do not allow the complete conversion of the fuel mixture, while for R_1>87% the lower oxygen availability entails increasing CO emissions, as reported in previous works [7]. Instead, CO emissions of the Burner 2 are always about 10^4 ppm, independently of the investigated bypass ratio of the Burner 1. In this respect, too short residence times characterize Burner 2, thus entailing incomplete fuel oxidation. Therefore, in order to obtain a complete combustion and reduce the CO emissions for Burner 2, a further system configuration with Burner 2 inlet flow bypass, as though for Burner 1, was investigated (Figure 4).

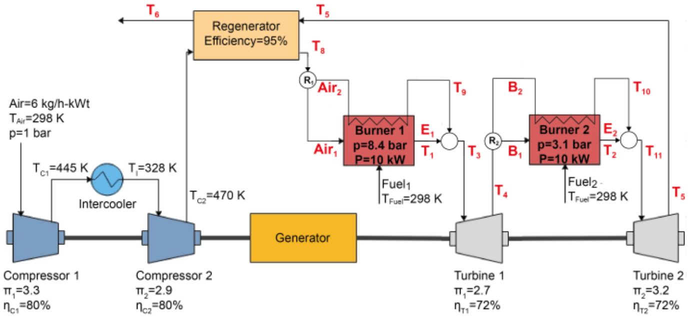

Figure 4. *Scheme2: System configuration with Air bypass for both the burners.*

In this respect, the bypass ratio R_1 was set equal to 87%, identified as optimal operative condition for Burner 1. In particular, results reported in Figure 5 highlight operative temperatures and emission levels for Burner 2 as a function of the bypass ratio (R_2) coherent to the ones obtained for Burner 1.

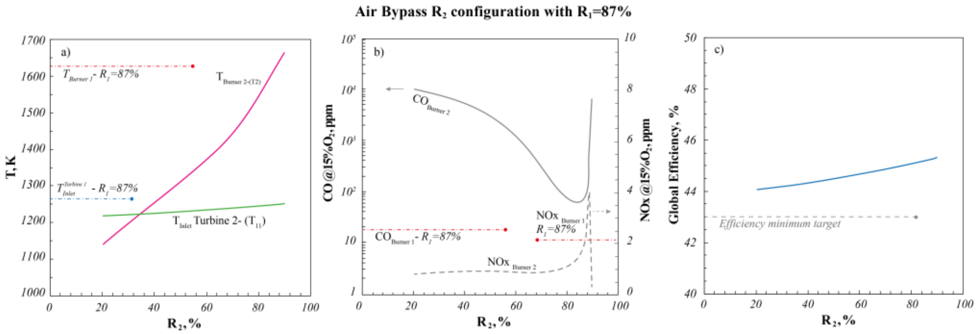

Figure 5. *Scheme 2: Operative T (a), CO-NO$_x$ emissions (b), global efficiency (c) vs %R$_2$. R$_1$=87%.*

In particular, by providing a bypass ratio for Burner 2 equal to R_2=85% stable and complete combustion is achieved, with inlet temperature for turbine 2 of about 1240 K, while CO and NO_x emissions keep lower than 60 ppm and 2 ppm, respectively. Furthermore, the Bryton system configuration with bypass for both the burners and bypass ratios R_1=87% and R_2=85% allows to achieve a global efficiency equal to 45% (Figure 5c), thus meeting the minimum required target (>43%). Therefore, such a configuration is identified as the optimal one to ensure stable combustion and suitable operational temperatures, while minimizing both CO and NO_x emissions and meeting the intercooled-reheat-regenerative Bryton system operative requirements.

Conclusion

In the proposed work the reheating process in a low-power, intercooled, regenerative and reheated gas turbine plant was analyzed. By the analysis of different configurations, the best operating conditions for methane combustion have been outlined. In particular, the plant configuration with bypass systems for both the burners and bypass ratios R_1=87% and R_2=85% ensures stable combustion and minimized pollutant emissions, with a global efficiency of about 45%. The methodology developed has led to interesting results especially for the use of alternative energy carriers such as ammonia or low-grade fuels, thus leading to the optimization of operative conditions with respect to the combustion process.

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