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A Thermodynamic Study of Pressure Gain Combustion in Combined Cycles

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Abstract. Gas turbines are internal combustion engines based on the Brayton-Joule cycle with four thermodynamic processes including air compression, constant pressure combustion, gas expansion and heat rejection. Actually, a relevant increase in entropy production is related to the constant pressure combustion, even in the ideal cycle, so alternative combustion solutions, such as the Pressure Gain Combustion (PGC), are worthy of attention.
This work aims at investigating PGC potential in gas turbines compared to conventional power plants based on the Brayton-Joule cycle. Both simple cycle and combined cycle operations are considered, focusing on a F-class gas turbine unit for power production. Cycle performance is estimated through a thermodynamic in-house code, where the common calculation scheme has been revised in order to simulate a combustion process occurring with increasing pressure from inlet to outlet of the combustor. A booster compressor is necessarily included in the power system for delivering the cooling air to the first stage blades of the turbine. The results are fully satisfactory as PGC technology really improves the efficiency of the gas turbine expander: in case of a pressure gain of 45%, which is a reasonable value based on literature data, 1.3 to 3.4 percentage points more in gas turbine efficiency have been calculated. Finally, a parametric analysis of expansion efficiency penalties due to supersonic pulsating flows at the first stage of the turbine expander is presented.

1. Introduction

Nowadays, gas turbines play a key role in several industry fields, most of them crucial for the world economy. From a thermodynamic point of view, gas turbines are internal combustion engines based on the Brayton-Joule cycle. In a gas turbine, four thermodynamic processes must be considered: (i) air compression, (ii) constant pressure combustion, (iii) gas expansion and (iv) heat rejection. Even in the ideal Brayton-Joule cycle, the constant pressure combustion causes a relevant increase in terms of entropy production. Thus, alternative solutions to the constant pressure process have been proposed by many researches and a group of them, namely the Pressure Gain Combustion (PGC), seems to be the most promising [1-3]. PGC means an unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure (conventional combustion incurs a total pressure loss) and allowing work extraction by expansion to the initial pressure. Accordingly, PGC has the potential to increase the propulsion efficiency of aero-engines as well as the thermal efficiency of stationary gas turbines. Up to date, detonative combustion processes have been the primary method to realize pressure gain combustion, such as pulsed and rotating detonation combustion, with the latter gaining more attention [4, 5].

The ideal thermodynamic cycles that model gas turbines with pressure gain combustion are the Humphrey and the Zel'dovich, von Neumann and Döring (ZND) cycles, presented in Figure 1 along with the reference Brayton-Joule cycle. The Humphrey cycle models gas turbines with ideal constant volume combustion and is best suited for the cases of shockless explosion combustion and resonant pulsed combustion. On the other hand, the ZND cycle models the application of detonative combustion in gas turbines.

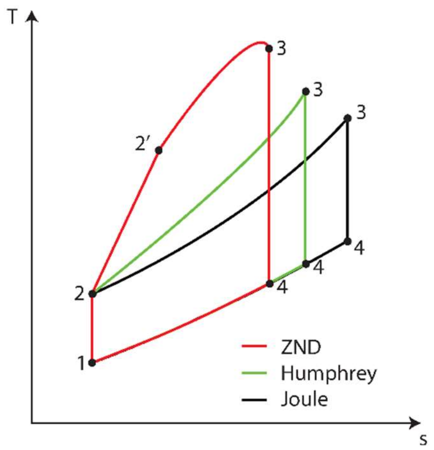

Figure 1. Comparisons of T-s diagrams of the Brayton-Joule, Humphrey and ZND cycles [6].

A theoretical demonstration of PGC potential to improve the efficiency of gas turbines was proposed by Heiser and Pratt [1]. Focusing on both the ideal Humphrey and ZND cycles, they concluded that the main reason for the higher cycle efficiency is the lower entropy increase during combustion. However, their cycle calculations did not model the actual physical phenomena in pressure gain combustion systems in a satisfactory way and the assumption that expansion starts at the highest temperature of the cycle (point 3 in Figure 1) is questionable [6].

Actually, the gas stream exiting the pressure gain combustor is characterized by strong pressure, temperature and velocity fluctuations [7]. The main challenge in the practical implementation of PGC into gas turbines is the lack of turbomachinery that can efficiently harvest work from the PGC exhaust gas. As a matter of fact, it is generally accepted that conventional turbine expanders have a lower isentropic efficiency when they interact directly with pressure gain combustors [8, 9]. Two extreme methods can be adopted in order to address this challenge. According to the first, a plenum or combustor outlet geometry could be designed to adapt the exhaust stream from the pressure gain combustor to an extent that it could be fed to a conventional turbine. In this case, the latter would operate at its design efficiency. The other approach focuses on a dedicated turbine design that could directly expand the exhaust stream from the pressure gain combustor. However, optimizing the combination of a pressure gain combustor outlet geometry and an adapted turbine design would be a much more rational approach to achieve the maximum possible work extraction.

The current work aims at studying and highlighting the possible advantages of pressure gain combustion in improving the thermal efficiency of stationary gas turbines. As a matter of fact, pressure gain combustion is an interesting technology not only for propulsion applications but also for gas turbines in combined cycle lay-outs as reported by Gulen [10] and by Dubey et al. [11]. In detail, the current work is based on a parametric analysis focusing on increasing pressure gain values as well as different amounts of air for combustion chamber cooling. Referring to a base case, represented by a F-class gas turbine, the effects of pressure gain combustion are investigated as a measure to reduce the load of the main compressor. Thus, the current study does not keep the pressure ratio at the compressor fixed, as schematically shown in Figure 1 and the calculations are performed by simulating the turbine expander with almost the same calculation hypotheses of the base case. Accordingly, the pressure ratio at the compressor is reduced thanks to the pressure gain in the combustion chamber, but an air booster is now necessary to properly feed, at the due pressure level, the blade cooling circuits at the first stage of the turbine. In addition, a penalty in the expansion efficiency of the first stage of the turbine is also introduced to make the analysis as general as possible.

2. Simulation environment and assumptions

The PGC cycles are simulated by using a proprietary code developed by the Gecos Group at Politecnico di Milano, known as GS ('Gas Steam'). GS is a modular simulation code designed to solve the energy balance at the design point of various plant configurations, representing them as networks of components, including compressors, combustors, expanders, heat exchangers, mixers, splitters, etc. The software iteratively solves the mass, energy balances and constitutive equations of each component until the design specifications imposed by the user are met, reaching stable convergence. The in-house code GS has been successfully used in past works by the authors to calculate a variety of power plant configurations, including gas and steam turbines [12-14], integrated coal gasification systems as well as advanced power generation systems including CO_2 capture [15-20]. While extensive explanations and validations of the simulation code can be found in previous works from the research group [12, 13], this section provides a quick overview of its main features.

The GS software adopts the ideal gas model for all gas mixtures and assumes a 0-D model for the compressor, where the average polytropic efficiency is evaluated based on the size parameter of the turbomachinery. The combustor is modelled as a full conversion reactor, ensuring the complete combustion of fuel species into H_2O and CO_2. The cooled expander is a component with a significant impact on modern gas turbine performance and is modelled by the 1-D approach proposed by Chiesa and Macchi [12]. This model enables the calculation, row by row, of geometric, aerodynamic and thermodynamic characteristics of the streams and incorporates a physical approach to model the cooling system. The turbine model has been validated for various commercial advanced large-size heavy-duty gas turbines, as documented in other papers [12-14].

Table 1. Ranges of design parameters and performance specs of F-class gas turbines by Ansaldo Energia, General Electric – GE Vernova and Siemens Energy.

Number of turbine stages	3 - 4
Gross GT power output, MW	288 - 385
Gross GT efficiency, %	38.7 - 41.9
Pressure ratio	16.9 - 21
GT exhaust mass flow rate, kg/s	662 - 800
GT exhaust temperature, °C	593 - 621
Net CC plant output, MW	443 - 570
Net CC plant efficiency, %	60 - 62.2

In detail, a proper set of assumptions has been used to evaluate the performance of the commercial gas turbines of three different manufacturers, namely Ansaldo Energia, General Electric – GE Vernova and Siemens Energy, as listed in Table 1. Design parameters and performance specs are taken from [21] and checked against websites of the respective manufacturers. GS simulations were run by imposing the number of turbine stages, pressure ratio and exhaust mass flow rate. The turbine inlet temperature (TIT), defined as total temperature at the first rotor inlet and not usually declared by the manufacturers, is varied to match the turbine outlet temperature (TOT).

Based on the results of the validation of the GS estimation and manufacturer's data for power output and efficiency in simple and combined cycle operations, the technological level of the F-class gas turbines is accurately described by an average value of TIT = 1430 °C. Hence, this value has been used to evaluate the performance specs of the reference gas turbine and the corresponding combined cycle, as reported in Table 2 along with the main design parameters.

Table 2. Main design parameters and resulting performance specs of the F-class gas turbine and combined cycle.

Gas turbine	
Pressure ratio at the compressor	19
Air temperature at compressor outlet, °C	427.9
Turbine inlet temperature (total temperature at the first rotor inlet), °C	1430
Exhaust flue gas mass flow rate, kg/s	750
Exhaust flue gas temperature, °C	597.1
Electric power output at generator terminals, MW	334.8
Electric efficiency, %	40.67
Bottoming steam cycle	
HP/RH evaporation pressure, bar	166/36
HP/RH temperature at turbine admission, °C	565/565
Condensation pressure, bar	0.04
Flue gas temperature at stack exit, °C	85.0
Steam turbine power output at generator terminals, MW	162.3
Combined cycle	
Electric power output, MW	494.6
Electric efficiency, %	60.09

3. PGC cycle performance evaluation

The evaluation of the performance of a combined cycle with pressure gain combustion at the gas turbine is set up by assuming that the pressure at turbine inlet remains unchanged compared to the reference case. This means the effect of pressure gain combustion is accounted for by reducing the pressure ratio at the compressor. This choice, rather than increasing the turbine inlet pressure at the same compressor pressure ratio, is justified for two main reasons.

1) Feasibility: the turbine operates under the same conditions as the reference power plant, simplifying implementation. In a multistage axial compressor, typical of gas turbine engines, achieving a lower pressure ratio is straightforward by eliminating one or more high-pressure stages.
2) Maximum efficiency in combined cycle mode: assuming a fixed TIT, increasing the turbine inlet pressure reduces the TOT. While this improves the efficiency of a simple gas cycle, it is detrimental to a combined cycle, since the latter benefits from converting the heat

released in the gas turbine exhaust into work. Typically, the efficiency of a combined cycle is optimized at the pressure ratio that maximizes the specific work of the gas turbine, which is typical in single-shaft heavy-duty gas turbine design.

From a computational standpoint, rotating detonation combustion is modeled as a device that increases flow pressure while maintaining the enthalpy balance of the component. The pressure increase achieved in the PGC system necessitates modifications compared to traditional systems, as schematically illustrated in the plant flow diagram in Figure 2. As a matter of fact, the air pressure at the main compressor outlet is insufficient for cooling the hottest sections of the turbine. Consequently, a booster compressor is required to elevate this flow (denoted as #4 in Figure 2) to an adequate pressure. The latter was assumed to be 19.11 bar throughout the simulations, matching the compressor outlet pressure of the reference cycle (see Tables 2 and 3). The air flow processed by the booster compressor also includes an additional portion (stream #3 in Figure 2) for the following purposes.

- Ensuring the cooling of the combustor liner. This stream is necessary for a technical reason and eventually mixes with the main stream.
- Diluting the main flow rate to reduce the gas temperature at the exit of the PGC system, aligning it with the target TIT. With a constant TIT, the gas temperature at the exit of the PGC system rises as the dilution flow rate increases, potentially enhancing the pressure gain, which is proportional to the temperature ratio in the combustion process (see next Figure 4).

The impact of these two flows on the thermal balance of the system and the temperature ratio of the rotating detonation combustion is identical. Therefore, they are combined in the simulation without distinguishing between the individual flow rates.

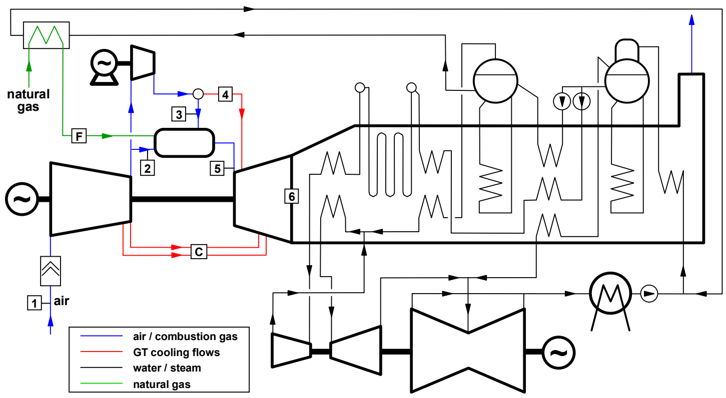

Figure 2. Plant flow diagram of the combined cycle based on the F-class PGC gas turbine.

4. PGC cycle results and discussion

This section reports the results of a parametric analysis oriented to highlight the advantages when exploiting PGC in a F-class gas turbine fuelled with natural gas (CH_4 89%, C_2H_6 7%, C_3H_8 1%, C_4H_{10} 0.1%, C_5H_{12} 0.01%, CO_2 2%, N_2 0.89%, with a lower heating value of 46.48 MJ/kg). In detail, a parametric analysis is carried out by considering increasing pressure gain in the combustion system and all the calculations are based on the assumptions that the combustor cooling flow rates (stream #3 in Figure 2) mix at the same stagnation pressure with the product gas, with no losses, before entering the turbine expander.

The first result is shown in Figure 3 and reports the trend of the temperature ratio (TR) during combustion as a function of the amount of coolant processed by the booster compressor (namely the ratio between stream #3 and the total air flow into the combustion chamber). Actually, the larger the coolant stream, the higher the TR, i.e. the combustion temperature, later reduced after dilution with the coolant before entering the gas turbine expander. The 'ref' line in Figure 3 stands for the base case with (almost) isobaric combustion by considering the actual combustor outlet temperature (COT). Of course, the temperature of the air flow rate at the main compressor outlet in the base case is higher due to the higher pressure ratio at the compressor. In order to better appreciate the results in Figure 3 and compare these preliminary trends with previous results of other researchers, literature results of pressure ratio vs. temperature ratio [22-26] are reported in Figure 4 [26]. For this study, only pressure gain combustor models are presented in Figure 4 for an implementation in 0-D gas turbine performance simulations. In general, the combustor outlet temperature is defined by the energy balance around the combustor. The main challenge for steady state performance simulations is to infer the combustor pressure ratio [25] which, according to the theory, lies in between a purely isobaric and ideal isochoric change of state. In detail, different models of pressure gain combustion were implemented by Paxson [22], Nalim [23], Goldmeer et al. [24], as well as the more recent 'Mix' model proposed by Neumann et al. [26], which matches published CFD data of Paxson [25]. As shown in Figure 4 [26], optimistic and pessimistic versions are also included for this 'Mix' model. Red segments highlight the results of the current study, as anticipated in Figure 3, compared to previous literature models: especially the case of pressure gain (PG) equal to 45% is fully consistent with the most recent model by Neumann et al. [26].

Based on the considerations above, performance results of the power cycles are presented in Figures 5 to 8. Although the cases of pressure gain (PG) equal to 25% and 65% are too pessimistic and optimistic, respectively, based on the temperature ratios included in Figure 4 from previous studies, they are useful to outline next theoretical trends in Figure 5 and below. The potential of PGC technology is clear, regardless of the pressure gain value under consideration. Focusing only

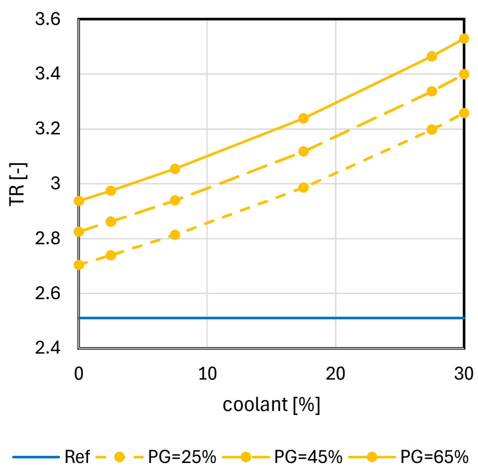

Figure 3. Temperature ratio (TR) trend for three values of pressure gain as a function of the amount of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber).

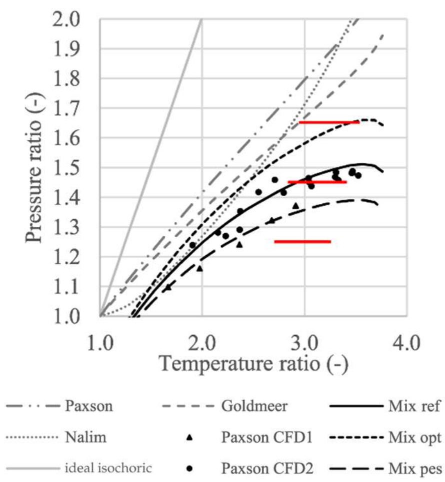

Figure 4. Pressure ratio vs. temperature ratio according to some literature models [26] and red segments transferring the results in Figure 3. The limits of each segment refer to the amount of coolant (0% on the left and 30% on the right).

on the gas turbine, i.e. the topping cycle, the trend is justified by considering that the higher the pressure gain during combustion, the lower the load of the main compressor. Actually, the increasing power demand of the booster compressor with the pressure gain is not detrimental to overall GT performance. As regards the decreasing trend of the GT power output, and consequently of the GT efficiency, the larger the coolant, the higher the load of the booster compressor for a fixed PG. Just focusing on the pressure gain at 45%, the power demand of the booster compressor rises from 4.5 to 23.7 MW for the coolant spanning from 0 to 30%. On the other hand, when considering an increasing pressure gain (from PG = 25% to PG = 45% and then to PG = 65%), the improvement in GT performance is initially clear, then less significant. As a matter of fact, the optimistic case with PG = 65% is characterized with a pressure ratio of 11.17 at the main compressor and the corresponding air pressure is not sufficient for cooling the rotor blades at the first stage of the turbine. Thus, the booster compressor has to deliver air to the turbine expander for cooling not only the first stator blades but also the first rotor blades.

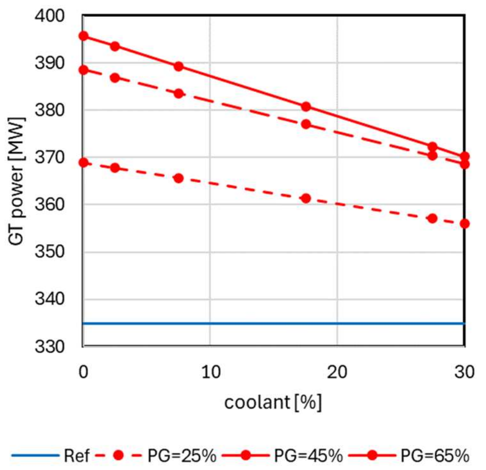

Figure 5. Gas turbine (GT) power output depending on the pressure gain (PG) and the amount of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber) compared to the reference base case.

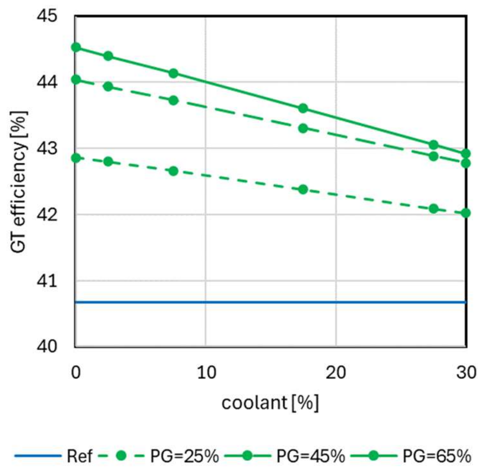

Figure 6. Gas turbine (GT) efficiency depending on the pressure gain (PG) and the amount of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber) compared to the reference base case.

Table 3 details temperatures, pressures and mass flow rates of the main streams in Figure 2 regarding the gas turbine, with reference to three specific cases. Among the various data, it is possible to appreciate that a slightly larger fuel input is necessary for the PGC cases, because of the lower temperature at the main compressor outlet, for the same energy balance with the fixed TIT. When calculating the GT efficiency (see Figure 6), this result must be taken into account, even though no serious influence on the GT efficiency trends can be appreciated compared to the reference base value.

Focusing on the combined cycle (CC) results, Figure 7 reports the same trend anticipated in Figure 5. As a matter of fact, based on the calculation assumptions for the gas turbine, the power output at the bottoming cycle is unchanged. The CC efficiency in Figure 8 is always higher than the reference base case, but the efficiency differences in Figure 8 appear to be somewhat reduced in comparison with the same cases in Figure 6.

Table 3. Temperatures, pressures and mass flow rates of the main streams in the schematic in Figure 2 for the F-class gas turbine selected as the reference base case and for two PGC cases: streams #1 to #4 are air, streams #5 and #6 are gas, F is fuel and C is air as the GT cooling flows except for the first stator blades.

	Reference base case			PG = 45% and coolant = 0%			PG = 45% and coolant = 30%		
stream	T, °C	p, bar	ṁ, kg/s	T, °C	p, bar	ṁ, kg/s	T, °C	p, bar	ṁ, kg/s
1	15.0	1.01	732.3	15.0	1.01	731.0	15.0	1.01	731.5
2	427.9	19.11	581.4	350.5	12.79	582.9	350.5	12.79	407.0
3	-	-	-	-	-	-	446.9	19.11	174.4
4*	427.9	19.11	38.9	446.9	19.11	41.6	446.9	19.11	43.1
5	1486.7	18.54	599.1	1488.9	18.54	601.9	1491.4	18.54	599.9
6	597.1	1.05	750.0	600.4	1.05	750.0	599.6	1.05	750.0
F	220.0	70.0	17.7	220.0	70.0	18.0	220.0	70.0	18.0
C	variable	variable	106.5	variable	variable	101.0	variable	variable	101.4

* As regards the reference base case, this flow rate is extracted at the compressor outlet, so temperature and pressure are the same as for stream #2

As anticipated, the results in Figures 5 to 8 regard an unchanged behaviour of the gas turbine expander compared to the reference base case. However, the PGC system delivers a strongly non-uniform flow and conventionally designed turbines may be inadequate in these conditions, with reduced expansion efficiency. For this reason, Mushtaq et al. [9] performed a preliminary design of a supersonic turbine and revealed that expansion efficiency values over 70% are possible. Thus, another parametric analysis has been conducted in the current study, in order to take into account possible variations in efficiency of the first stage of the turbine. In detail, the cooled expander in the GS software has been revised in order to introduce a fixed penalty in the expansion efficiency of the first stage. Compared to the efficiency value (90.55%) of the first stage, as calculated for the F-class gas turbine assumed as base case, reductions of 15 and 25 percentage points have been considered.

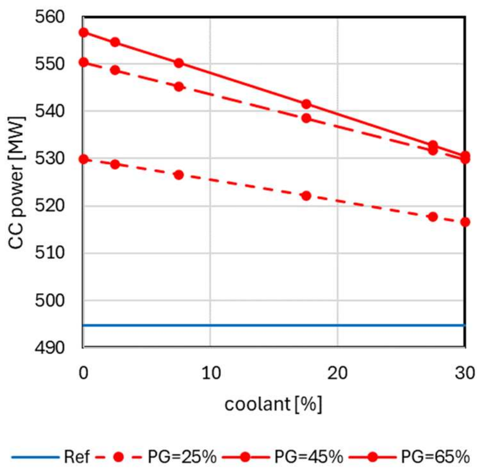

Figure 7. Combined cycle (CC) power output depending on the pressure gain (PG) and the amount of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber) compared to the reference base case.

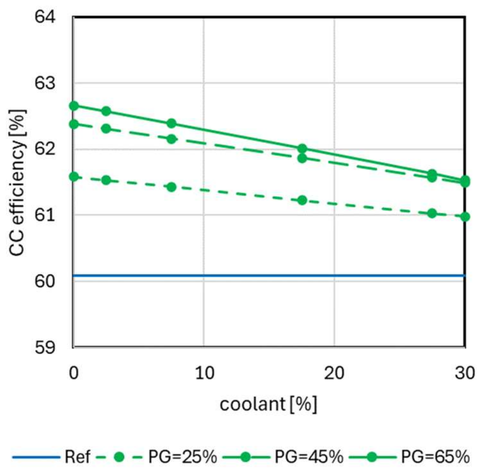

Figure 8. Combined cycle (CC) efficiency power depending on the pressure gain (PG) and the amount of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber) compared to the reference base case.

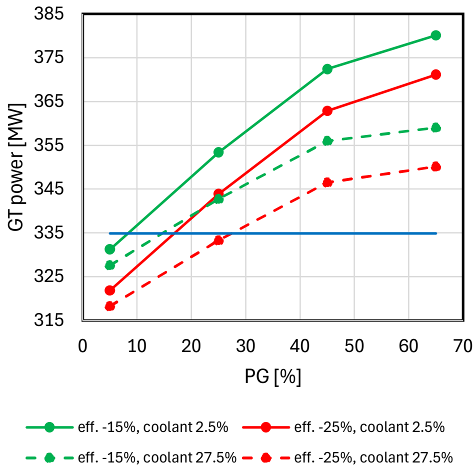

Figure 9. Gas turbine (GT) power output as a function of the pressure gain (PG) with two levels of efficiency penalty and two amounts of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber). The reference base case is included for a quick comparison.

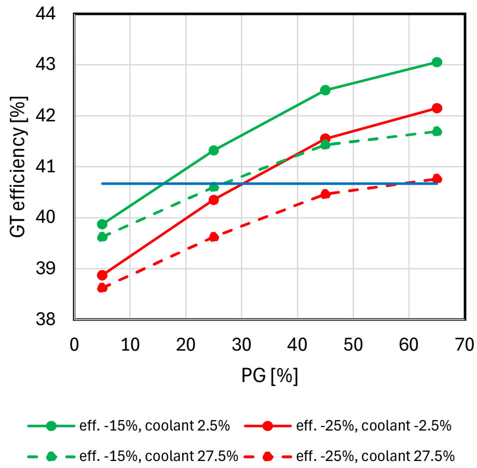

Figure 10. Gas turbine (GT) efficiency as a function of the pressure gain (PG) with two levels of efficiency penalty and two amounts of coolant at the combustion chamber (i.e. the ratio between stream #3 in Figure 2 and the total air flow into the combustion chamber). The reference base case is included for a quick comparison.

New results for GT power output and efficiency are shown in Figures 9 and 10, respectively, as depending on the pressure gain. In particular, two levels of efficiency penalty (-15% and -25%) as well as two amounts of coolant at the combustion chamber (2.5% and 27.5%) are considered. Referring to a PG value of 45%, a first glance at Figure 9 suggests higher GT power output than the refence base case, even with the highest penalty in the first stage efficiency and the largest amount of coolant. As already highlighted in Figure 5, switching from PG = 45% to PG = 65% is accomplished with larger flow rate through the booster compressor for blade cooling, so the GT power output improvements are a bit limited if compared to the cases switching from PG = 25% to PG = 45%. Nevertheless, when looking at Figure 10, it is possible to appreciate the efficiency trends position themselves differently from the power output trends compared to the reference value. This result is justified by referring to the slightly larger fuel amount necessary for the PGC cases, as anticipated in Table 3. A number of points in Figure 9 are better than the reference value, but the corresponding fuel inputs arrange GT efficiency points as in Figure 10. A general conclusion is not certainly immediate and attention should be paid to the overall CC performance. As a matter of fact, the exhaust gas at the inlet of the heat recovery steam generator increases (from around 600°C up to around 620°C) because of the penalty in the first stage turbine efficiency. This result, along with the constant gas flow rate, reflects on slightly higher power output at the bottoming cycle. In particular, with PG = 45%, coolant at 27.5% and efficiency reductions at the first stage of the turbine equal to -15% and -25%,

- CC power outputs of 522.8 and 516.9 MW, respectively, are calculated compared to 494.6 MW of the reference base case;
- CC efficiency of 60.84% and 60.36%, respectively, are calculated compared to 60.09% of the reference base case.

These data evidently suggest that the benefits achievable with PGC technology, as previously illustrated in Figures 5 to 8, can be seriously reduced without a dedicated turbine expander design.

5. Conclusion

This work has presented the results of some cases of pressure gain combustion applied in a F-class gas turbine for power production. Both simple cycle and combined cycle operations are investigated in comparison with conventional power plants. The results highlight the potential of PGC technology for improving the overall efficiency of the power plant. However, expansion efficiency penalties due to supersonic pulsating flows at the first stage of the turbine may seriously reduce the advantages of PGC technology. Thus, optimizing the combination of a pressure gain combustor outlet geometry and an adapted turbine expander design represents the most rational approach to achieve the maximum possible work extraction with the highest power plant efficiency.

6. Acknowledgements

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References

[1] Heiser W.H., Pratt D.T., Thermodynamic Cycle Analysis of Pulse Detonation Engines, J Propul Power 2002, 18(1):68-76, https://doi.org/10.2514/2.5899

[2] Nordeen C.A., Schwer D., Schauer F., Hoke J., Barber T., Cetegen B., Thermodynamic Model of a Rotating Detonation Engine. Combust Explos Shock Waves 2014, 50:568–577, https://doi.org/10.1134/S0010508214050128

[3] Neumann, N.; Peitsch, D. Potentials for Pressure Gain Combustion in Advanced Gas Turbine Cycles. Appl. Sci. 2019, 9, 3211. https://doi.org/10.3390/app9163211

[4] Wolanski P., Detonative Propulsion, Proc. Combust. Inst. 2013, 34(1):125-158, https://doi.org/10.1016/j.proci.2012.10.005

[5] Sousa J., Paniagua G., Collado Morata E. Thermodynamic Analysis of a Gas Turbine Engine with a Rotating Detonation Combustor, Appl Energy 2017, 195:247–256 http://dx.doi.org/10.1016/j.apenergy.2017.03.045

[6] Stathopoulos P., Comprehensive Thermodynamic Analysis of the Humphrey Cycle for Gas Turbines with Pressure Gain Combustion, Energies 2018, 11(12):3521, https://doi.org/10.3390/en11123521

[7] Ma F., Choi J.Y., Yang V. Thrust Chamber Dynamics and Propulsive Performance of Multitube Pulse Detonation Engines. J Propul Power 2005, 21(3):512-526, https://doi.org/10.2514/1.7393

[8] Suresh A., Hofer D.C., Tangirala V.E., Turbine Efficiency for Unsteady, Periodic Flows, J. Turbomach. 2012, 134(3):034501, https://doi.org/10.1115/1.4003246

[9] Mushtaq N., Colella G., Gaetani P., Design and Parametric Analysis of a Supersonic Turbine for Rotating Detonation Engine Applications, Int. J. Turbomach. Propuls. Power 2022, 7(1):1, https://doi.org/10.3390/ijtpp7010001

[10] Gulen S., Pressure Gain Combustion Advantage in Land-Based Electric Power Generation, J. Glob. Power Propuls. Soc. 2017, 1:288-302, https://doi.org/10.22261/K4MD26

[11] Dubey A., Sorce A., Stathopoulos P., A Comprehensive Thermodynamic Analysis of Gas Turbine Combined Cycles with Pressure Gain Combustion Based on Humphrey Cycle, Proceedings of the ASME Turbo Expo 2024, 24-28 June 2024, London, UK

[12] Chiesa P., Macchi E., A Thermodynamic Analysis of Different Options to Break 60% Electric Efficiency in Combined Cycle Power Plants, J Eng Gas Turbine Power 2004, 126(4):770–785, https://doi.org/10.1115/1.1771684

[13] Martelli E., Girardi M., Chiesa P., Breaking 70% Net Electric Combined Cycle Efficiency With CMC Gas Turbine Blades, Proceedings of the ASME Turbo Expo 2022, 13-17 June, Rotterdam, The Netherlands, https://doi.org/10.1115/GT2022-81118

[14] Gazzani M., Chiesa P., Martelli E., Sigali S., Brunetti I., Using Hydrogen as Gas Turbine Fuel: Premixed Versus Diffusive Flame Combustors, J Eng Gas Turbine Power 2014, 136(5):051504, https://doi.org/10.1115/1.4026085

[15] Giuffrida A., Moioli S., Romano M.C., Lozza G., Lignite-Fired Air-Blown IGCC Systems with Pre-Combustion CO_2 Capture, Int J Energy Research 2016, 40(6):831-845, https://doi.org/10.1002/er.3488

[16] Moioli S., Giuffrida A., Romano M.C., Pellegrini L.A., Lozza G., Assessment of MDEA Absorption Process for Sequential H_2S Removal and CO_2 Capture in Air-Blown IGCC Plants, Applied Energy 2016, 183:1452-1470, https://doi.org/10.1016/j.apenergy.2016.08.155

[17] Zaabout A., Romano M.C., Cloete S., Giuffrida A., Morud J., Chiesa P., Amini S., Thermodynamic Assessment of the Swing Adsorption Reactor Cluster (SARC) Concept for Post-Combustion CO_2 Capture, Int J Greenhouse Gas Control 2017, 60:74–92, https://doi.org/10.1016/j.ijggc.2017.03.001

[18] Cloete S., Giuffrida A., Romano M., Chiesa P., Pishahang M., Larring Y., Integration of Chemical Looping Oxygen Production and Chemical Looping Combustion in Integrated Gasification Combined Cycles, Fuel 2018, 220:725-743, https://doi.org/10.1016/j.fuel.2018.02.048

[19] Cloete S., Giuffrida A., Romano M.C., Zaabout A., The Swing Adsorption Reactor Cluster for Post-Combustion CO_2 Capture from Cement Plants, Journal of Cleaner Production 2019, 223:692-703, https://doi.org/10.1016/j.jclepro.2019.03.109

[20] Cloete S., Giuffrida A., Romano M.C., Zaabout A., Heat Pump-Driven Adsorption CO_2 Capture for Simple and Cost-Effective Retrofits of Coal Power Plants, Applied Thermal Engineering 2024, 236:121456, https://doi.org/10.1016/j.applthermaleng.2023.121456

[21] Gas Turbine World, 2021 GTW Handbook, vol. 36. A Pequot Publication, 2021

[22] Paxson D.W., A General Numerical Model for Wave Rotor Analysis, NASA TM 105740, 1992, https://ntrs.nasa.gov/citations/19920022240

[23] Nalim M.R., Thermodynamic Limits of Work and Pressure Gain in Combustion and Evaporation Processes, J. Propuls. Power 2002, 18(6):1176–1182, https://doi.org/10.2514/2.6076

[24] Goldmeer J., Tangirala V., Dean A., System-level performance estimation of a pulse detonation based hybrid engine, J. Eng. Gas Turbines Power 2008, 130(1):011201, https://doi.org/10.1115/1.2771246

[25] Paxson D.E. A Simplified Model for Detonation Based Pressure-Gain Combustors, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 25 - 28 July 2010, Nashville, TN, USA, https://doi.org/10.2514/6.2010-6717

[26] Neumann N., Woelki D., Peitsch D., A Comparison of Steady-State Models for Pressure Gain Combustion in Gas Turbine Performance Simulation, Proceedings of Global Power and Propulsion Society, 16–18 September 2019, Beijjing, China, https://gpps.global/wp-content/uploads/2021/02/GPPS-BJ-2019_paper_198.pdf