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Thermal Analysis and Performance of a Pressure Gain Combustion System

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Abstract

Conventional gas turbine engines burn fuel in a steady state combustor at constant pressure, and the pressure rise is obtained by the compressor driven by the turbine. In the Pressure Gain Combustion cycle, the combustion process is at constant volume, allowing an increase of the pressure without the need of the compressor. The process is not steady, and some difficulties arise to study it, in particular when one tries to join this unsteady process with a steady system, like a conventional gas turbine engine. In this work some characteristics of *PGC* system are studied, focusing on the possibility to raise the thermal efficiency of the whole system. Through a numerical program a thermal analysis of the system is performed, computing the main performance and efficiency.

Nomenclature

T: temperature
Q_{in}: heat for unity of mass introduced at constant volume in the combustion chamber
Q_{out}: heat for unity of mass released
U: internal energy
H: enthalpy
c_p: constant pressure specific heat
c_v: constant volume specific heat
γ: specific heat ratio
L: turbine work
L_c: compressor work
L_{net}: output work
m: mass
η_c: compressor adiabatic efficiency
η_t: turbine adiabatic efficiency
β_c: compressor pressure ratio
PGC: Pressure Gain Combustion
HPC: high pressure compressor
HPT: high pressure turbine

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1. Introduction

Modern gas turbine engines work following the classic Brayton thermal cycle, consisting in particular of a combustion process at constant (nearly) pressure. In these engines the pressure increase is completely performed by the compressor, absorbing a great amount of power by the turbine. However a gas turbine engine can work with a constant volume combustion process. At the beginning of the last century some gas turbine engines with constant volume combustion were built [1,2]. The main characteristic of this engine is that the pressure raise is due mainly to the combustion process, and hence Pressure Gain Combustion. In fact, the pressure inside the closed combustion chamber raises following the temperature increase. With the years this gas turbine engine was not further developed, leaving place to the Brayton turbine, that is still now the universal working cycle of gas turbine engines. The main difficulties with the constant volume combustion turbine were in the complex distribution system, completely mechanic, with not many possibilities to be adjusted to optimize the engine efficiency. Now, new interest arises on this subject for the potential benefits this turbine can have on the thermal efficiency [3,4]. Moreover, considering the new electronic control system of the engine, the operation capabilities can greatly improve. To evaluate the benefits in terms of performance and efficiency of a *PGC* system, a simulation numerical code has been developed. The code computes the working cycle of a gas turbine engine with constant volume combustion, and, once defined the cycle, it computes the main engine performances, in particular specific output power and thermal efficiency.

2. Thermal analysis

The thermal cycle of a *PGC* system is shown in fig. 1. It is composed by an adiabatic compression (1-2), an heat introduction (combustion) at constant volume (2-3), an adiabatic expansion (3-4), and an isobaric heat rejection (4-1). This cycle is often referred in literature as Humphrey (or Atkinson) cycle. In the same graphic is reported the Brayton cycle (1-2-5-6-1) , the common gas turbine working cycle, where the heat introduction takes place at constant pressure.

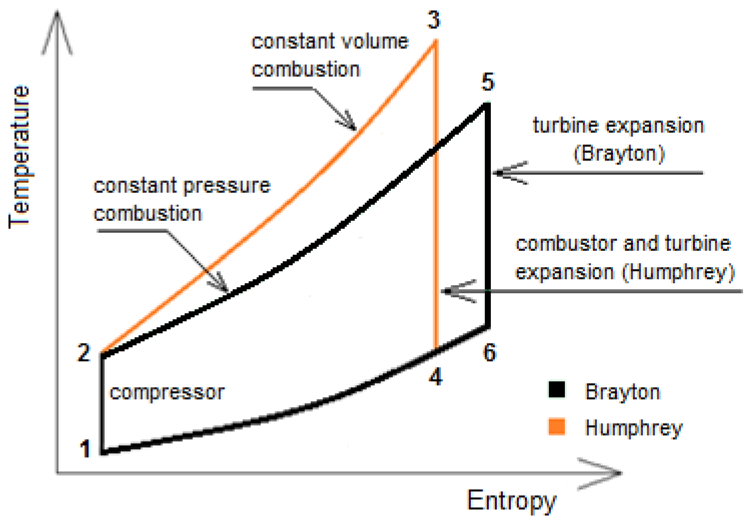

Fig. 1 Brayton and Humphrey thermodynamic cycle in a Temperature/Entropy plane. The point 3 represents the gas pressure and temperature at the combustor exit and turbine inlet. It is not constant, but varies (reduces) for the expansion inside the combustor during the combustor blow down.

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As shown in the graphic, the main difference between the two cycle is the phase of the heat introduction. In fact, while in the Brayton cycle it is at constant pressure, in the Humphrey it is at constant volume. The main consequence is that in the Brayton cycle the pressure raise is obtained by means of the compressor, that increase air pressure to the maximum cycle level, in the Humphrey the pressure gain is due in part to the compressor, but for a large measure to the combustion process, that taking place in a closed volume, raises the pressure without the need of the compressor. This fact reduces the mechanical work to drive the compressor, allowing more output power. A possible scheme of a gas turbine engine with *PGC* is shown in fig. 2.

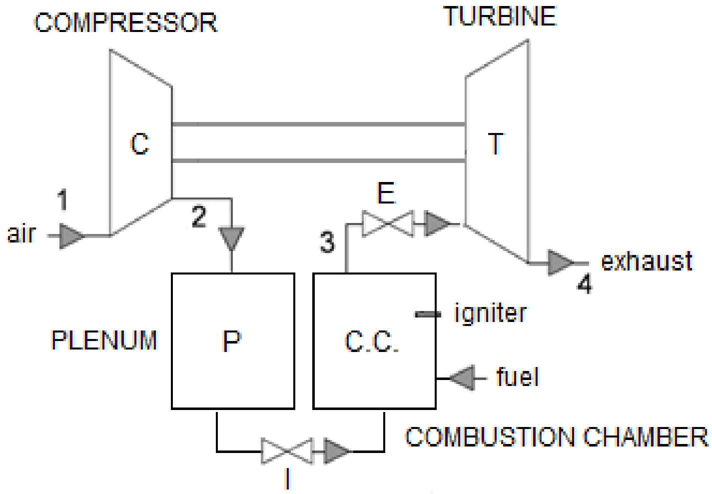

Fig. 2 Scheme of Pressure Gain Combustion gas turbine.

The system described in the picture works as follows: the air, at ambient conditions 1, enters the low pressure compressor **C** raising its temperature and pressure to condition defined at point 2. Then it enters the plenum P: it has the function to link the compressor (steady flow) with the combustion chamber (intermittent flow). From the plenum it fills the combustion chamber **C.C.** passing through the intake valve **I**, while fuel is introduced by a nozzle. Once the chamber is completely filled, intake valve **I** is closed and, started by igniter, combustion begins. Since it takes place in a closed volume both temperature and pressure raise, reaching their maximum value. When the combustion process is over, exhaust valve **E** opens, allowing gas to pass through turbine **T**, to drive the compressor **C**, and providing the output power. When combustion chamber has been evacuated, valve **E** is closed, valve **I** opens and the cycle starts again.

The first models of constant volume combustion turbine were used at the beginning of the last century to generate electric power. They were complex systems, and the following years the constant pressure combustion turbines took their place. The flow inside and outside the combustion chamber was controlled by mechanical valves, and their phasing was rather difficult. Nowadays the electronic control allows great flexibility in the engine parameter control and this, considering the potential benefit on the thermal efficiency, has renewed the interest in this system. One of the possible use of the *PGC* turbine is its coupling with a conventional gas turbine engine, replacing the high pressure section. In this case the high pressure compressor, the constant pressure combustion chamber and the high pressure turbine could be replaced by a single constant volume combustion chamber, with evident advantages [5-7]. The main difficult is to couple the low pressure compressor steady system with the intermittent flow of the combustion chamber and the turbine.

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The thermal efficiency of the system is the ratio of output power and heat introduced; referring to the scheme and the cycle of Figs. 1 and 2, the output power is represented by the difference between the turbine power and the power adsorbed by the compressor.

The heat for unity of mass, Q_{in}, introduced at constant volume in the combustion chamber, is equal to the gas internal energy variation between the points 2 and 3 in the graphic:

$$Q_{in} = U_3 - U_2 = c_v(T_3 - T_2) \qquad (1)$$

The heat for unity of mass released is the enthalpy variation between the points 4 and 1:

$$Q_{out} = H_4 - H_1 = c_p(T_4 - T_1) \qquad (2)$$

The expansion process is unsteady, and takes place both inside the combustion chamber and through the turbine at the same time. The pressure inside the combustion chamber is reduced as consequence of the hot gas mass flow through the outlet valve. Afterwards, the gas expands adiabatically in the turbine. The turbine is therefore unsteady, since the gas condition at the inlet vary with time. In particular the gas pressure at the turbine inlet is reduced, being equal to the gas pressure at the combustor exit. While the expansion in the turbine is adiabatic, it is difficult to say the same for the expansion inside the combustor, because a form of heat exchange with the combustor walls can occur. In this work, it is assumed that this expansion is adiabatic too. The first part of the gas from the combustor enters the turbine at the maximum cycle temperature and pressure and expands to the ambient pressure. A second part of the gas enters the turbine at a lower temperature and pressure, since they have been reduced inside the combustor, but also this gas mass flow fraction expands to ambient pressure. The third part of mass flow behaves in the same way, but starting from lower pressure, and so on until the inlet pressure is reduced to the lowest pressure and there is no expansion through the turbine. So the expansion has been divided in intervals and for each interval the work of the single mass flow rate has been computed, and then summed. If the expansion in the turbine is divided in N intervals, and indicate L_i the turbine work done in each interval, the total work L is the sum:

$$L = \sum_{i=1}^{N} L_i \qquad (3)$$

It is interesting to notice that, although the different gas mass flow fractions have different values of pressure and temperature at the turbine inlet, they have the same pressure (ambient) and temperature at the turbine exit, due to the fact that the expansion in both the combustor and the turbine is adiabatic. The number N of intervals in which the turbine expansion is divided in is a critical aspect for the computation of the turbine work. Some simulations were performed, and the value of 10 intervals was chosen [8]. In fact no sensible improvements in the result accuracy is observed for greater numbers of intervals. The net work L_{net} available at the turbine shaft is the difference between the turbine work and the compressor work L_c:

$$L_{net} = L - L_c \qquad (4)$$

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The compressor operates in steady state condition, and its work is therefore given by:

$$L_c = \frac{1}{\eta_c} m c_p T_1 \left(\beta_c^{\frac{\gamma - 1}{\gamma}} - 1 \right) \quad (5)$$

The thermal efficiency of the system is the ratio of the net work and the heat introduced:

$$\eta_{th} = \frac{L_{net}}{Q_{in}} \quad (6)$$

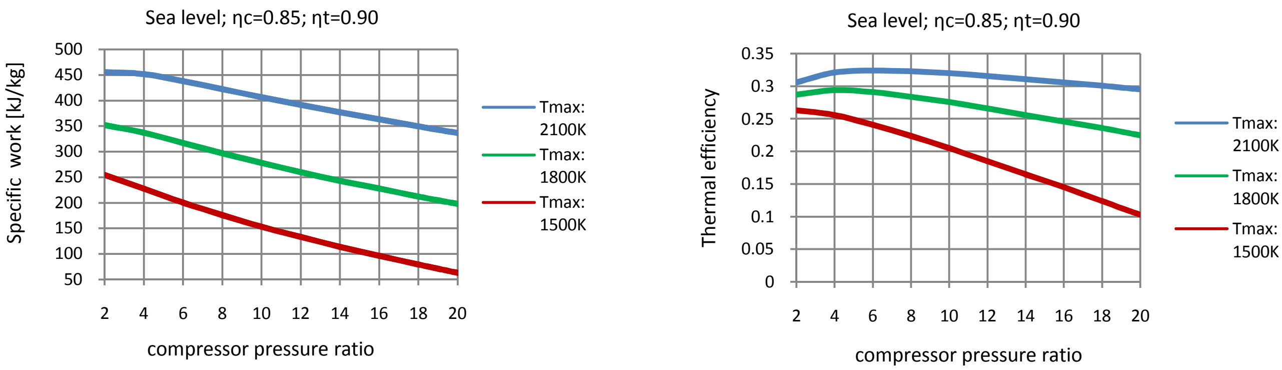

Fig. 3 Specific work and thermal efficiency of *PGC* computed with the simulation thermodynamic program. Three maximum cycle temperatures have been investigated: 1500K, 1800K and 2100K. The compressor efficiency η_c is 0.85, while the turbine efficiency η_t is 0.90. The performance are computed at sea level condition, and the engine has no forward velocity.

By means of a the thermodynamic numeric code the output specific work and the thermal efficiency have been computed. Three combustion temperatures have been selected, respectively 1500K, 1800K and 2100 K, being representative of low, medium, and high level of combustion temperature. The external conditions are sea level pressure and temperature, and no velocity of the engine has been considered. As previously said, the expansion process has been divided into 10 intervals, and different compressor and turbine efficiency have been considered. The turbine efficiency must be chosen carefully for the non steadiness of the flow. In the graphics of fig.1 and Fig.2 are reported the behavior of the output power and thermal efficiency. We can notice that the output power increases with the maximum combustion temperature, and decreases with the compressor pressure ratio. This because the compression work rises with pressure ratio reducing the available output work. At higher temperatures the graphic shows a maximum at very low pressure ratio, indicating an optimum pressure ratio value.

Also the thermal efficiency increases with maximum temperature, and decreases with pressure ratio. The graphics show a maximum, more evident at high temperatures, at low pressure. If we consider the curves at 2100 K, we see that the output

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power maximum is at about 2 of pressure ratio, while the thermal efficiency maximum is at about 6. We can say that in this case there is a narrow pressure ratio interval where both power and efficiency have the best performance.

As shown by the graphics, the maximum temperature reached in the constant volume combustion chamber can be sensibly higher than those the turbine can withstand. In the first models of the Holzwarth turbine [9], at the beginning of '900, every "hot" cycle was followed by a cold cycle, without combustion, just to cool the combustor valves and the turbine. However, the gas temperature at the turbine inlet is not constant during a cycle, because during the combustor blow down the gas expands inside the combustor reducing the turbine inlet temperature. With reference to the cycle of fig.1 we can say that the point 3, considered as the gas temperature at the combustor exit and turbine inlet, moves down following (as first approximation) the adiabatic/isentropic expansion 3-4. For this reasons the turbine operates at a mean temperature lower than the maximum combustion temperature, and could withstand it. The turbine must work at high temperature and in unsteady conditions. In fact, since the gas expands inside the combustion chamber, the pressure, temperature and velocity at the turbine inlet vary with time, and this can have influence on the turbine efficiency if compared with a steady case. In fig.4 is reported the variation of power and thermal efficiency as function of the turbine efficiency η_t.

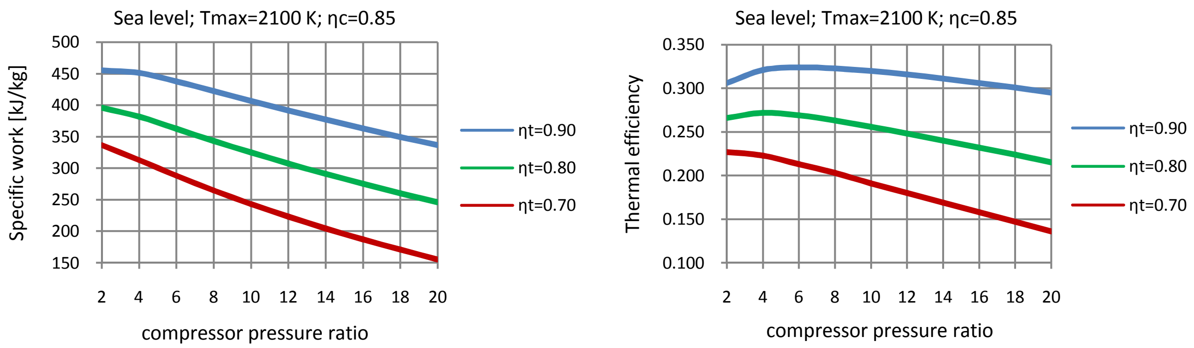

Fig. 4 Specific work and thermal efficiency of *PGC* turbine computed for different values of the turbine efficiency: $\eta_t = 0.70$; 0.80 and 0.90. The cycle is computed at sea level, Tmax=2100 K, and compressor efficiency $\eta_c = 0.85$.

The value of the turbine efficiency becomes critical to obtain high levels of power and thermal efficiency. In fact if the turbine efficiency is below a certain level then the performance becomes too poor. The risk that turbine efficiency could be too low comes from the fact that it does not work in steady condition. Not many experimental results about unsteady turbine efficiency are available, so it is not easy to simulate its behavior. However, some works [10-12] indicates that also with pulsed flow the turbine efficiency does not fall dramatically respect to the steady case.

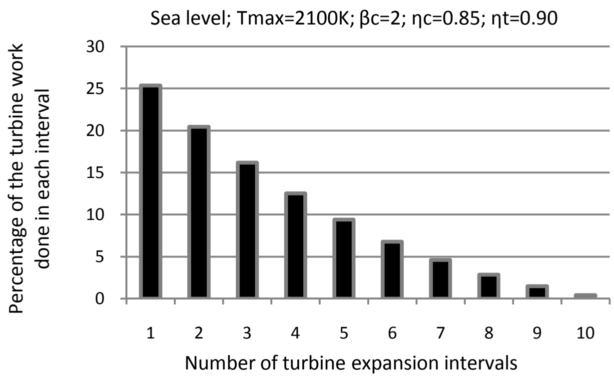

Fig. 5 Percentage of the work done in each part the turbine sub-expansion.

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In fig.5 is reported the work done in every single sub-expansion the turbine expansion has been divided in. It is interesting to notice as the largest part of the work is developed in the first part of the expansion, while in the last part the percentage of the work done is very low. In the case reported in Fig.5, during the first 5 parts of the expansion about the 84% of the whole work is developed. This suggest that, describing the unsteady expansion of the turbine, a more detailed computation should be done for the first part of the expansion, while a less detailed simulation of the last part do not lead to great errors.

3. Conclusions

Some features of a *PGC* turbine engine have been studied by means of a thermodynamic program that allows to simulate the working cycle and compute the main performances, in particular the specific work and the thermal efficiency. The program describes the unsteady turbine process dividing the whole expansion in different (10) sub-expansions, and computes the whole turbine work as the sum of the work done in each sub-expansion. The results show that a *PGC* system can have good level of specific power and thermal efficiency despite the unsteady flow. The condition to attain good performances is to reach high combustion temperatures, but this can cause problems regarding the possibility for some component, like combustion chamber, exhaust valve and turbine, to withstand those severe working conditions. However, the intermittent nature of the flow could mitigate the gas peak temperature, similarly to what happens in piston engines. Otherwise a cooling system for those stressed component should be provided. Another important aspect is the turbine efficiency. From the graphics is shown that if it is too low, both specific work and thermal efficiency remain at low levels. The matter is still open, because there are not many numerical or experimental results that can answer this question. However, some experimental results regarding some tests on unsteady turbines, say that its efficiency could be not so lower than a steady turbine. The *PGC* turbine engine is a relatively simple and cheap (no high pressure rotating parts) system that can successfully use to produce power. One of the possibility to use this system in an aero engine is to top a gas turbine replacing the high pressure section (HPC, combustion chamber and HPT) with a *PGC* system. In this case great advantage in terms of weight and costs can be attained but, as already said, the main difficult is to tune an unsteady flow system with a steady one. From the analysis done, it comes that the combustion process, and the unsteady turbine behavior are certainly the most critical aspects of the system to be investigated in deep.

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