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Main Performances of the Unsteady Constant Volume Combustion Thermodynamic Cycle

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Abstract

Common gas turbine engine work following the constant pressure combustion Brayton thermodynamic cycle. In the Humphrey cycle, heat is instead introduced at constant volume, allowing the pressure rise without the need of the compressor. The reduction of the compressor work can rise the thermal efficiency, however the process unsteadiness can mitigate these benefits. By means of a thermodynamic numerical program, a comparison of the main features of the two cycle, in particular specific output work and thermal efficiency, is done, focusing on the main effects that the unsteady combustion and expansion can have on the performance, and on the problems that can arise when joining steady and unsteady intermittent flow components.

Nomenclature

T:	temperature
Q_{in}:	heat for unity of mass introduced at constant volume in the combustion chamber
c_p:	constant pressure specific heat
γ:	specific heat ratio
L:	turbine work
L_c:	compressor work
L_{net}:	output work
m:	mass
η_{th}:	cycle thermal efficiency
τ:	temperature ratio (T_3/T_1)
β_c:	compressor pressure ratio
CVC:	Constant Volume Combustion

1. Introduction

The continuous research of high efficiency and low emission gas turbine engines has brought the engineers to consider novel approaches for next future engines. In the years, the engine efficiency has been enhanced mainly rising the maximum

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cycle temperature and the pressure ratio, but this trend cannot be followed indefinitely, and some changes in the working cycle must be done. In this sense, different options are on the table, among them regeneration, staged-intercooled compression and constant volume combustion are promising alternatives. In this paper we are going to show some features of a constant volume combustion (CVC) gas turbine engine, in particular the main performances, the integration with a conventional gas turbine engine, and the limits imposed by the unsteadiness of the thermal cycle. In fig. 1 is reported the thermal cycle of the CVC gas turbine (Humphrey cycle) and the conventional gas turbine cycle (Brayton cycle) as reference. The main difference between the two cycles is the heat introduction phase, that in the Brayton cycle is at constant pressure, while in the Humphrey at constant volume. The combustion in a closed volume allows pressure to rise without the need of compression work, and this can lead to higher thermal efficiencies. Some gas turbines with constant volume combustion, used for the production of electric power, were built in the first years of '900 by the german inventor H. Holtzwarth [1,2]. They were complex machines, and after some years they were replaced by Brayton cycle gas turbine engines. However, due to the thermal efficiency capability, there is new interest in this cycle, also considering the flexibility that the engine could have thanks to modern electronic control [3,4].

To compute the performances of a CVC engine, a numeric program that solves the Humphrey cycle has been developed. The code, written in FORTRAN, computes the main performances of the thermal cycle for different operating conditions.

2. Numerical analysis

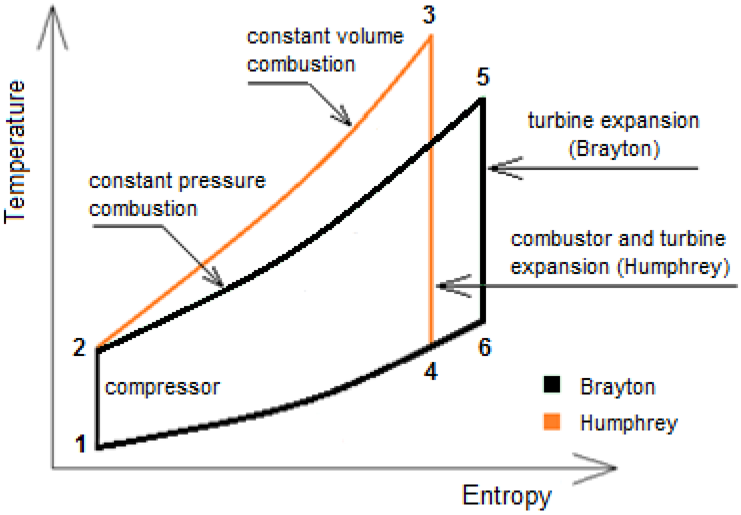

Fig. 1 Brayton and Humphrey thermodynamic cycle in a Temperature/Entropy plane. The point 3 represents the gas pressure and temperature at the combustor exit and turbine inlet. It is not constant, but varies (reduces) for the expansion inside the combustor during the combustor blow down.

In fig. 1 is shown the ideal CVC thermal cycle. It is composed by an adiabatic compression (1-2), an isochoric heat introduction (combustion) (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 as reference the Brayton cycle (1-2-5-6-1) , the common gas turbine working cycle, where the heat introduction takes place at constant pressure.

As previously said, the main difference between the two cycle is the heat introduction process. In the Humphrey cycle, as consequence of the heat introduction at constant volume there is a significant pressure rise, similar to what happens in the internal combustion engine. Since the pressure rise is achieved without the compressor work, this can have a positive impact on the thermal efficiency. While the thermal efficiency of the ideal Brayton cycle depends only on the pressure ratio:

$$\eta = 1 - \frac{1}{\beta_c^{(\gamma-1)/\gamma}} \tag{1}$$

in the Humphrey cycle it depends also on the temperature ratio τ, as shown in the equation (1):

$$\eta = 1 - \gamma \left\{ \frac{\left(\tau / \beta_c^{(\gamma-1)/\gamma}\right)^{1/\gamma} - 1}{\tau - \beta_c^{(\gamma-1)/\gamma}} \right\} \tag{2}$$

In fig 2 are reported the graphics of the thermal efficiency of an ideal Humphrey and a Brayton cycle, as function of the pressure ratio, as obtained by equations (1) and (2).

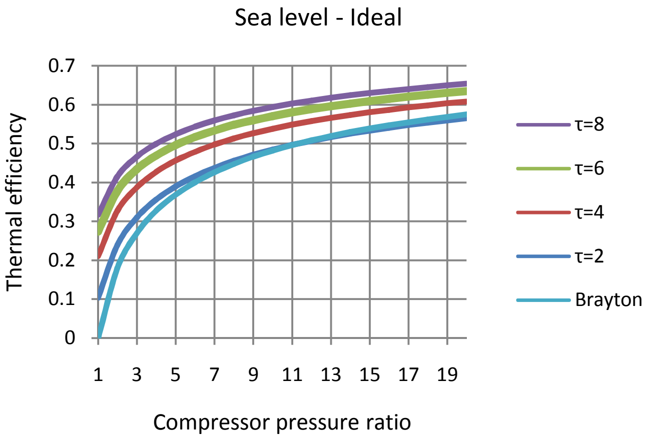

Fig.2. Thermal efficiency as function of pressure ratio of a Humphrey ideal cycle at different τ values, and an ideal Brayton as reference.

The Brayton cycle is inherently steady: the gas turbine is a steady engine, and also the constant pressure combustion phase is continuous, time independent. The Humphrey cycle instead, since the combustion takes place in a closed volume, can be performed in an unsteady engine. The flow through the combustion chamber is intermittent, and consequently also the flow through the turbine is unsteady, and this leads to different works and thermal efficiency respect that calculated through eq. (2), obtained for a steady Humphrey cycle.

At the end of the combustion process the gas properties are those indicated by point 3 of the graphic of Fig.1. When the discharge valve opens, gas blows out from the combustor, enters the turbine inlet and expands through the turbine developing the expansion work. During the combustor blowdown (not instantaneous) as the first gas fraction passes through the exhaust valve, the mass inside the combustor reduces, and gas inside the combustor expands. For this reason, during combustor blowdown the pressure and temperature of different gas fractions at the turbine inlet reduce with time,

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while in the Humphrey steady cycle they are constant and are represented by point 3 of fig.1(maximum cycle pressure and temperature). Since the heat introduced is the same for steady or unsteady cycle, the thermal efficiency of the latter will be lower. To compute the gas properties at the turbine inlet is necessary to know which kind of expansion takes place inside the combustor during blowdown. It is difficult to know that exactly, because different aspects are involved. In our case, as first approximation, we will consider the expansion inside the combustor as adiabatic isentropic, of the same type of that through the turbine

3. Unsteady cycle

If we consider the expansion inside the combustion chamber and the turbine as adiabatic-isentropic, it will be represented by expansion 3-4 on the graphic of fig.3. As consequence, during the blowdown the gas conditions at the turbine inlet will be represented by a point on that line: the first gas fraction by point 3, the other fractions by point (7) at low pressure and temperature on that line, tending to point 4 for the last mass fraction. To simulate the behavior of an unsteady Humphrey cycle gas turbine engine, a numerical program has been developed.

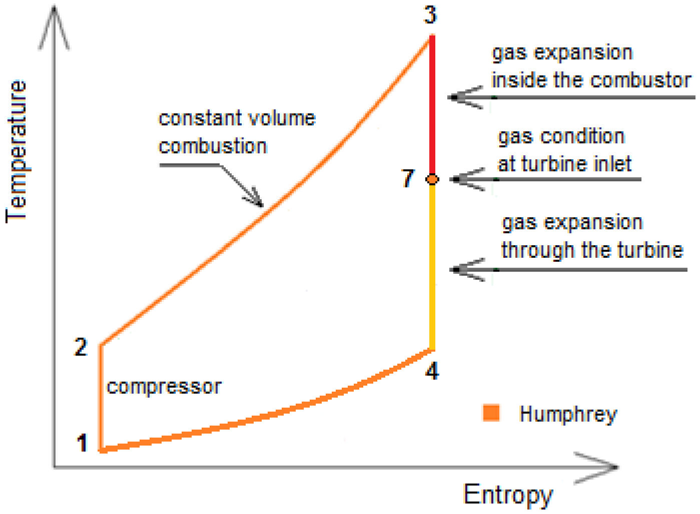

Fig.3. Gas expansion in unsteady Humphrey cycle. The gas expansion takes place both in the combustor and in the turbine. The point 7 represents gas conditions at the turbine inlet after the combustor blowdown. Since the expansion inside the combustor and turbine are adiabatic isentropic, the point 4, representing gas conditions at the turbine exit, is the same for all gas mass fractions.

The program solves the cycle for different engine (maximum temperature, pressure ratio, efficiencies, specific heat) and operating conditions (external pressure and temperature), allowing to compute the main performances, as specific output work, thermal efficiency and specific fuel consumption. To simulate the unsteady turbine work, the expansion has been divided into parts and computed the initial condition of each mass fraction (point 7 of fig.3), the work done by each fraction is the enthalpy drop from point 7 (variable) to point 4 (constant), and the whole work as sum of the work of each fraction. 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:

$$L = \sum_{i=1}^{N} L_{\mathrm{i}} \tag{3}$$

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The net output work is the difference between the turbine work and the compression work:

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

Where:

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

We must notice that while the turbine is an unsteady component, the compressor works in steady conditions. Hence there is the need to match the two components by means of an intermediate volume. The thermal efficiency is then computed as:

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

In graphic of Fig.4 is reported the behavior of the thermal efficiency of the ideal-unsteady Humphrey cycle for different values of τ .

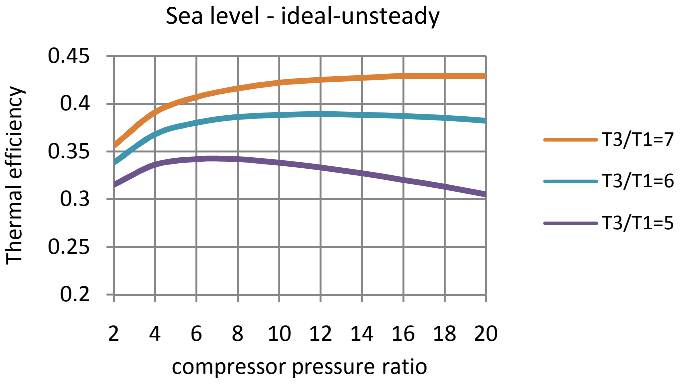

Fig.4. Thermal efficiency as function of compressor pressure ratio of an Humphrey ideal-unsteady cycle at different temperature ratios T_3/T_1. The turbine unsteadiness has been considered dividing the expansion in 10 parts, and computing the work as the sum of each work fraction.

The turbine expansion has been divided into 10 parts, the work of each mass fraction computed and then summed to obtain the whole expansion work [5]. If we compare these graphics with those of Fig.2 we notice as in the case of unsteady cycle, the thermal efficiency is considerably lower than in the case of steady cycle. The reason, as previously said, is the reduced enthalpy drop available for the unsteady power turbine due to the combustor blowdown. We must consider also that we have made the hypothesis that the expansion inside the combustor is adiabatic (and isentropic in the ideal case). This assumption could be verified, and the expansion-blowdown process in the combustor studied more in details.

4. Conclusions

A numerical program that studies the main thermodynamic characteristics of a constant volume combustion gas turbine engine has been developed. In particular, the program computes the thermal efficiency and the output work of an ideal

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Humphrey cycle. The program simulates the unsteady turbine expansion, dividing it in intervals, computing the gas thermodynamic characteristics at each interval, and the output work as the sum of the work of each mass fraction. The main result is the significant difference between the work and the thermal efficiency in case of steady or unsteady Humphrey cycle. In fact, while the performance of the steady cycle are higher than the conventional Brayton cycle, considered as reference, the performances are lower if the unsteadiness is taken into account. Since the pressure rise is mainly obtained during combustion, the maximum cycle temperature becomes critical to attain high level performances. An important aspect is the expansion inside the combustor during blowdown. It has been considered as first approximation adiabatic isentropic, but it should be investigated more in details because it greatly influences the output power and then the thermal efficiency, Other improvements should be done in simulating the unsteady expansion. It is the first part of the expansion that greatly affects the output power, while the last fractions do not influence it much. So the first part should be simulated with shorter computation intervals. Passing from the ideal to real cycle, the adiabatic efficiency of the unsteady turbine must be carefully considered, for its effect on the performance and efficiency of the cycle. Some experimental studies indicate however that the efficiency of unsteady turbines does not fall dramatically [6-8].

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