PERIODIC-COMBUSTION GAS TURBINE ENGINES (UNITS)

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Glossary

1. Introduction

At the beginning of the 20th century in the early gas turbine engines (GTE) the cycle with combustion at constant pressure (p = const) and cycle of periodic combustion (PC) with rising of pressure were employed. The first industrial units p = const, because of great losses in the turbine and compressor, had low efficiency. It has forced the designers and scientists to work above the normal use in GTE of a PC cycle. The experimental plant of V.V.Karavodin with the one-valved chamber PC has indicated the possibility of making GTE without any compressor.

In plants of G. Holzwarth with two-valved chamber the periodic combustion was implemented at constant specific volume (v = const). These plants created during 1908-1925, had efficiency up to 20 % and rated power up to 2600 kW. Despite rather high parameters, owing to some demerits, plants of Holzwarth have not found applications in industry.

After significant improvement of compressors and turbines at the end of the 1930s the industry again became engaged in development GTE with p = const, and the cycle of PC has found narrow application only in aircraft pulse jet engines and in some special applications.

However the main advantage of a PC cycle with the possibility of increased efficiency and specific power of GTE, remains unexploited, therefore interest in it continues. In Russia research works on this cycle were conducted under the supervision of B. Stetshkin, V. Uvarov, N. Inosemtsev, G. Giritsky, S. Shnee, N. Riasantsev, V. Mikhaltzev and others at different times. Theoretical and experimental works were conducted in some research and educational institutes, and design offices of plants.

In England, France, USA, and in other countries investigations on both cycle as a whole, and process of PC were conducted (F. Reynst, R. Marchal, L. Edelman, H. Heitland, G. Mangold, H.v.d Meulen and others).

Their investigations show, that the application of GTE with PC in some fields can be considerably profitable. It concerns the elementary GTE with low pressure ratio and gives an increase of power and efficiency without changing of the mass of the unit.

2. GTE of Periodic Combustion with Three-valved and by Two-valved Chambers

2.1 GTE Design

In Figure 1 the design of one of the first GTEs with three-valved chambers with combustion at v = const (G. Holzwarth) with the additional steam turbine (ST), water pump (WP) and condenser (Cd) raising total efficiency of the unit is shown.

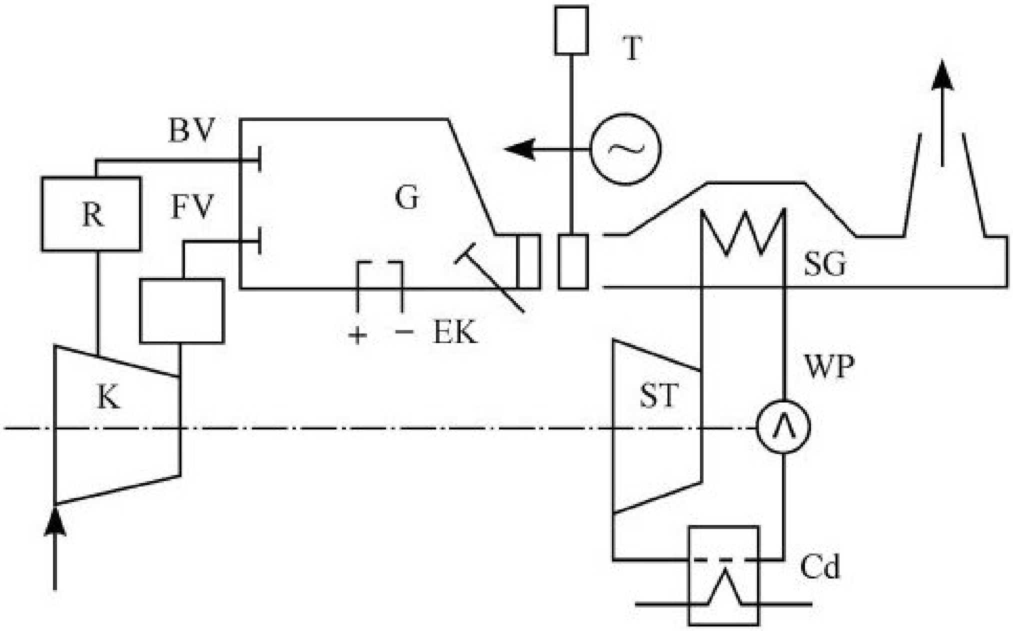

Figure 1: GTE with three-valved chambers, combustion at constant volume with the additional steam turbine (ST), water pump (WP) and condenser (Cd)

In such a unit for cleaning of the chamber from combustion products emergent through the exit valve (EV) the scavenging air of low pressure (Figures 1 and 2a) gets to the chamber G through a blow-down valve (BV) during the period Z_B.

After blowing through the compressor C fills the chamber G with air through BV at pressure p_k (Figures 1 and 2a) during the period Z_f , when the valves BV and EV are closed.

In accordance with filling of the chamber the pressure in it increases and by the end of filling Z_H the chamber pressure reaches p_k.

At this moment the fuel introduced into the chamber is fired by the spark from a spark-plug and burns at closed valves during time Zq.

As combustion of fuel takes place, the heat is generated at constant specific volume, the temperature of the gas increases up to T_G and the pressure - up to p_G. At the end of combustion EV opens and the gas expands in the turbine during time Z_V, and streams through steam generator SG.

Thus the chamber pressure decreases up to p_B, which is a little bit more of counter pressure behind the turbine $p_T \cong p_A$. After that the BV is opened and the cycle is repeated.

The ideal Holzwarth cycle is shown as *p*-*v* diagram, where the specific power of the cycle is equivalent to the area AKGT (Figure 3).

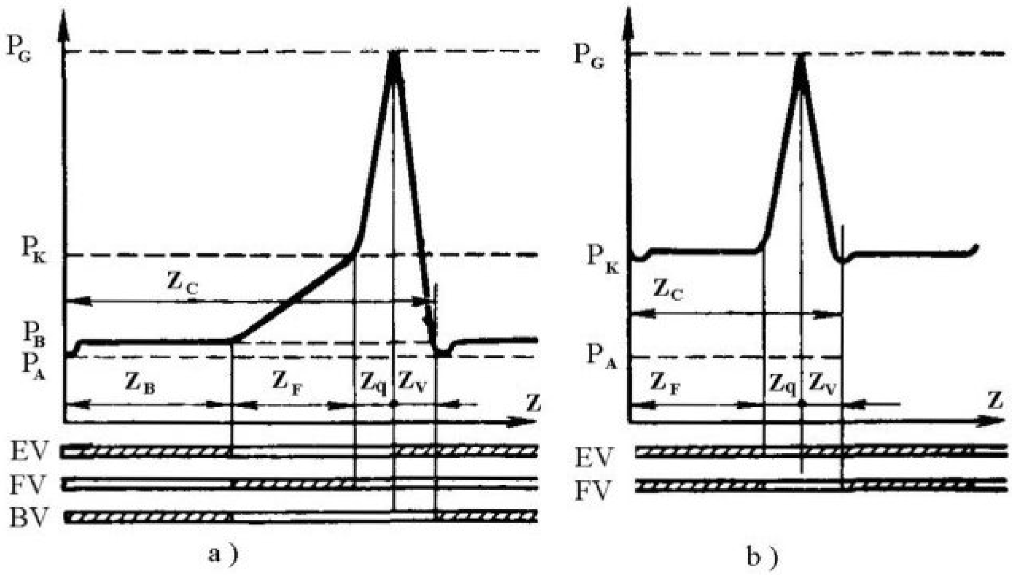

Figure 2: The temporal character of processes in GTE with three-valved chambers, combustion at constant volume with the additional steam turbine (ST), water pump (WP) and condenser (Cd)

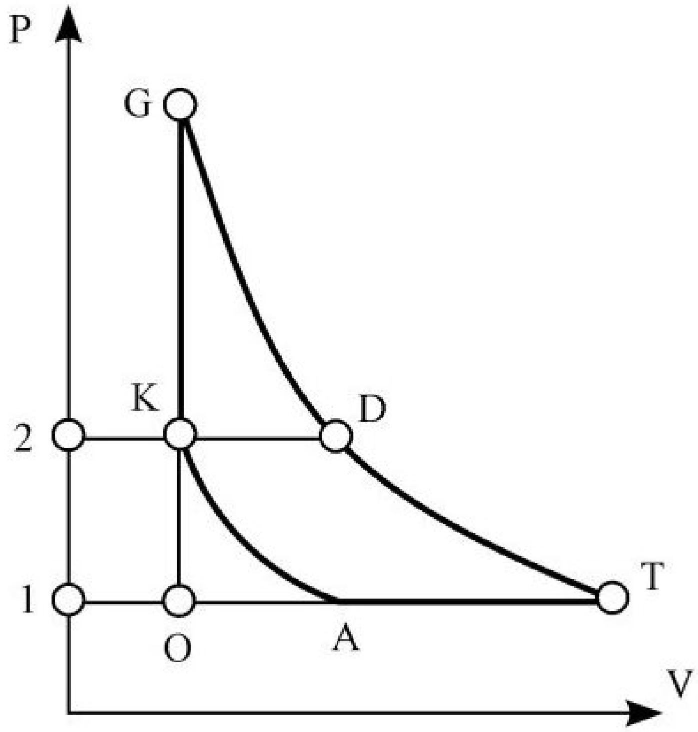

Figure 3: The ideal Holzwarth cycle

As the compression process takes place, the ideal compression process, accomplished through cooling, is an isotherm AK (in the case of compression without cooling the curve AK is an adiabat), the process of application of heat – by isochore KG and the process of expansion – by adiabat GT. The power of ideal processes of compression and filling of the chamber is equivalent to the area OAK, expansion power - of the area OGT. The plant operation on the Holzwarth cycle is related to design, gas dynamic and energy deficiencies. The vibrations of combustors and of the whole unit are the deficiencies of the design, as well as the small specified of operation EV, because of the severe working conditions. The exit valve in GTE as against the outlet valve of piston engines lets hot gas pass before its expansion at high temperature and density. Use of rotary distributive washers or spool-type mechanisms instead of valves in essence does not change the situation, but gives rise to extra difficulties connected with sealing of clearance at the effluxion of combustion products polluted with particles of unburnt fuel and ashes. Because of variable modes of their operation the low efficiency of blade machines is related to the character of gas dynamic deficiencies. At constant pressure p_T the turbine inlet pressure changes from pressure p_G up to pressure $p_B \cong p_T$, and the pressure ratio in the turbine changes from p_G/p_T up to unity. Thus the efficiency of the turbine changes from maximum value to negative, because, while scavenging of the chamber the turbine works as the gas brake. The compressor works also in off-design conditions. The receiver is necessary for reduction of pressure difference between the compressor and chamber.

The volume of the receiver decreases with increase of number of chambers due to their consecutive operation. The high losses arise because of throttling of air in FV during filling of the chamber after scavenging, when the difference between pressure in the receiver and the chamber is great, and also in the first period of gas efflux through the EV in the case of the great difference between pressures in the chamber and in front of the turbine. The small active period Z_A concerns deficiencies of energy character. An active period is only the period of expansion, i.e. $Z_A = Z_v$, which makes 10 — 15 % of time cycle Z_c. This leads to increase of the specific sizes of the turbine and of the plant as a whole. Useful power is generated by the gas turbine. Later Stodola and Shule proposed combustion in two-valved chamber without BV, not to scavenge the chamber by air of low pressure, but to charge it at opened FV and EV. In the Stodola cycle the filling of the chamber from the receiver begins at the moment, when the chamber pressure is reduced up to $p_D=p_k$ and occurs at constant pressure. The specific power of an ideal Stodola cycle is equivalent to the area AKGT (Figure 3), same, as for the Holzwarth cycle. The specific power of ideal compression is equivalent to the area 12KA, the power of ideal expansion is equivalent to the area 12KGT, i. e. both values of specific power are larger, than in the Holzwarth cycle, on identical quantity, equivalent to area 12KO. A GTE with v = const, working on the Stodola cycle has almost the same deficiencies, as for the Holzwarth cycle except for throttling of air in FV by filling of the chamber. GTE efficiency and specific power depend on profitability and character of processes of the cycle: compression in the compressor, filling of the combustor and expansion in the turbine.

2.2 Compression Process and Filling of Combustors

2.2.1 Filling of a Three-valve Combustor after Scavenging

The losses during filling of the combustor after scavenging depend on the number of receivers, from which the gas goes to chambers, and on the efficiency of the compressor.

Filling of the chamber from one receiver that contains the air with T_k and pressure p_k (Figure 4).

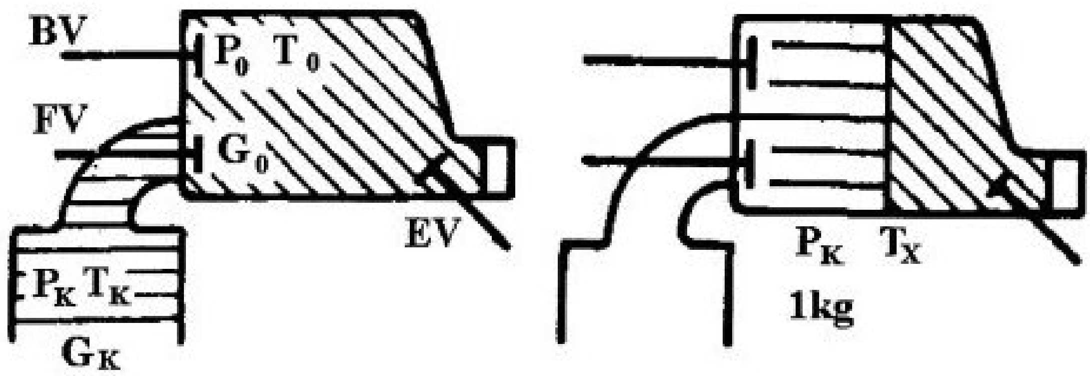

Figure 4: Filling and emptying of the chamber

At the beginning of filling in the chamber there is air after scavenging of mass G_0 at temperature T_0 and pressure p_0, and at the end of filling in the chamber of volume V mass of air of 1 kg at pressure p_k and temperature T_x. The mass entering from the receiver into the chamber $G_k = 1 – G_0 = 1- T_x\, p_0/(T_0\, p_k)$. The temperature T_x at the end of filling of the chamber is determined from expressions of the first law of thermodynamics, written for transition of system of mass 1 kg from state 1 to state 2 (Figure 4)

$$T_x = kT_k /(1 + k\frac{T_k}{T_0}\frac{p_0}{p_k} - \frac{p_0}{p_k}) \qquad (1)$$

Specific power of the compressor L_{kv}, necessary for filling of the chamber by air of mass 1 kg,

$$L_{kv} = L_k G_k \qquad (2)$$

$$L_{kv} = \frac{Rk}{k-1} T_A (\pi^{\frac{k-1}{k}} - 1)\frac{1}{\eta_{kv}}(1 - \frac{T_x}{T_0}\frac{p_0}{p_k}) \qquad (3)$$

Temperature T_x increases with rising of $\pi = p_k/p_0$ as temperature T_k is increased and as a result of rising of pressure at the subsequent filling of the chamber air is additionally heated. The power L_{kv}, decreases with growth of T_x because of diminution of mass of the fresh charge of air, and that is accompanied by the relevant lowering of expansion power and useful power of GTE.

Filling of the chamber from infinite number of receivers

At filling of the chamber from one receiver there are losses because of final, sometimes of considerable difference of pressure in the receiver and chamber during filling. It corresponds to throttling and leads to temperature rise of air in the chamber. The losses are reduced at diminution of the difference between receiver and chamber pressures. In the extreme case, when at each moment of filling the difference between receiver and chamber pressures is infinitesimal, the losses on throttling at filling tend to zero. Such filling will need infinitely big number of receivers and compressors with infinitesimal difference in pressures. At polytropic compression process in compressors after filling from all z receivers the chamber pressure will increase up to p_k, temperature of scavenging air — up to T_0, and temperature of the first portion of air - up to T_{1k} and so on, up to last portion, with temperature T_k.

Mean temperature of air in the chamber at pressure p_k at the end of filling from infinite number of receivers corresponds to temperature of an intermixture of all portions

$$T_{x\infty} = \frac{kT_k}{k\frac{T_k}{T_0}\frac{p_0}{p_k} + n[1-(1-\frac{p_0}{p_k})^{\frac{1}{n}}]}.$$

Then $T_{0k} < T_{\mathrm{x}\infty} < T_k$.

Specific power of the compressor $L_{k\mathrm{v}}$, necessary for filling of the chamber by air in amount 1kg at number of receivers $z \to \infty$,

$$L_{k\mathrm{v}\infty} = \frac{R}{k-1}T_{x\infty}\frac{p_A}{p_k}\{\frac{p_k - p_0}{p_A} - n[(\frac{p_k}{p_A})^{1/n} - (\frac{p_0}{p_A})^{1/n}]\}.$$

In that specific case for reversible filling of the chamber, when $n = k$, $T_\mathrm{x} = T_{k\mathrm{ad}}$ and $p_0 = p_A$, power of the compressor $L_{k\mathrm{v}\infty\mathrm{ad}} = u_{k\mathrm{ad}} - u_A - p_A(v_A - v_k)$, that is the power of reversible filling of the chamber GTE v = const corresponds to power of the process of reversible compression in a piston compressor.

Filling of the chamber from final number of receivers

At filling of the chamber from several receivers temperature of air in it is determined sequentially as when filling from one receiver and accordingly specific power of compressors is expressed as the total of its power. For example, at filling the chamber after scavenging from three receivers temperature $\mathrm{T_x}$ and the power $\mathrm{L_{kv}}$ of compressors without intercooling is determined after definition of power of each compressor and temperatures of air in the chamber at the end of filling from the relevant receiver. Specific power of compressors at compressing up to pressures p_k', p_k'', p_k''', is accordingly

$$L_k' = \frac{Rk}{k-1}T_A(\pi^{\frac{n-1}{n}} - 1);\ L_k'' = \frac{Rk}{k-1}T_A(\pi^{\frac{2(n-1)}{n}} - 1);\ L_k''' = \frac{Rk}{k-1}T_A(\pi^{\frac{3(n-1)}{n}} - 1).$$

Temperature of air in the chamber at the end of filling from the relevant receiver is

$$T_x^{'} = \frac{kT_k^{'}}{1+\frac{1}{\pi}(k\frac{T_k^{'}}{T_A}-1)}; \qquad T_x^{''} = \frac{kT_k^{''}}{1+\frac{1}{\pi}(k\frac{T_k^{''}}{T_x^{'}}-1)}; \qquad T_x^{'''} = \frac{kT_k^{'''}}{1+\frac{1}{\pi}(k\frac{T_k^{'''}}{T_x^{''}}-1)},$$

where p_k', p_k'', p_k''', T_k', T_k'', T_k''' are respectively pressures and temperatures in receivers, and pressure ratio in the next receivers are $\pi' = \pi'' = \pi''' = \sqrt[3]{\pi_k} = \pi$, where $\pi' = p_k'/p_A$, $\pi'' = p_k''/p_k'$, $\pi''' = p_k'''/p_k''$, and $\pi_k = p_k'''/p_A$.

The amount of air that is necessary to deliver to the chamber from the relevant receiver, so that in the chamber at the end of filling from the receiver to get 1 kg of air is

$$G^{'} = 1-\frac{1}{\pi}\frac{T_x^{'}}{T_A}; \qquad G^{''} = 1-\frac{1}{\pi}\frac{T_x^{''}}{T_x^{'}}; \qquad G^{'''} = 1-\frac{1}{\pi}\frac{T_x^{'''}}{T_x^{''}}.$$

The amount of air proceeding to the chamber from all receivers with mass of air 1 kg at the end of filling is

$G = G'(1 - G'')(1 - G''') + G''(1 - G''') + G'''$.

The aggregate specific power of the compressor referred to 1 kg of air in the chamber at the end of filling from the third receiver is

$$L_{kv} = L_k^{'}G^{'}(1-G^{''})(1-G^{'''}) + L_k^{''}G^{''}(1-G^{'''}) + L_k^{'''}G^{'''}.$$

Temperature of air in the chamber at the end of filling $T_x = T_x^{'''}$. With increase of number of receivers the temperature of air T_x and ratio T_{xz}/T_{x1} are reduced the pressure p_G at given temperature at the end of combustion increases, the mass of air in the chamber of given volume and the ratio G_z/G_1 also increase. All these phenomena lead to pinch of efficiency of GTE. Approximately the specific power L_{kvz} with z receivers depends on the power $L_{kv\infty}$: $L_{kvz} = L_{kv\infty}\xi$, where $\xi = f(z)$ practically does not depend on π in the interval of change $\pi = 4 \ldots 10$.

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