THERMODYNAMIC CYCLES OF ROCKET ENGINES

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Summary

Information about the thermodynamic cycles of rocket engines using chemical propellants and the thermal efficiency of the cycle are quoted. The difference of the performance of real processes in the rocket engine chamber from the ideal ones which leads to the losses during heat transformation into the jet kinetic energy is examined.

1. Introduction

All chemical rocket engines have two common characteristics:
- they utilize chemical reactions in a thrust chamber to produce a high-pressure, high temperature gas at the entrance to a converging-diverging exhaust nozzles;
- the hot propellant gas expands in flowing through the exhaust nozzle, and expansion process converts a portion of the thermal energy, released by the chemical reaction, into the kinetic energy associated with a high-velocity gaseous-exhaust jet.

2. Ideal cycle

The rocket engines using the chemical propellants are the thermal machines with a constant working agent flow and continuous process behavior. In the rocket engines, heat obtained from the combustion of rocket propellant is transferred into kinetic energy and results in a thrust.

The ideal cycle processes of heat transformation into work provide the fundamental principles of rocket engine operation. Such ideal thermodynamic cycle, with the heat input at a constant pressure and isentropic gas expansion is presented on "p - V" coordinates in Figure 1. It is assumed that the working agent is an ideal gas with constant heat capacity and invariable composition, and processes making up the cycle proceed without thermal or gas dynamic losses.

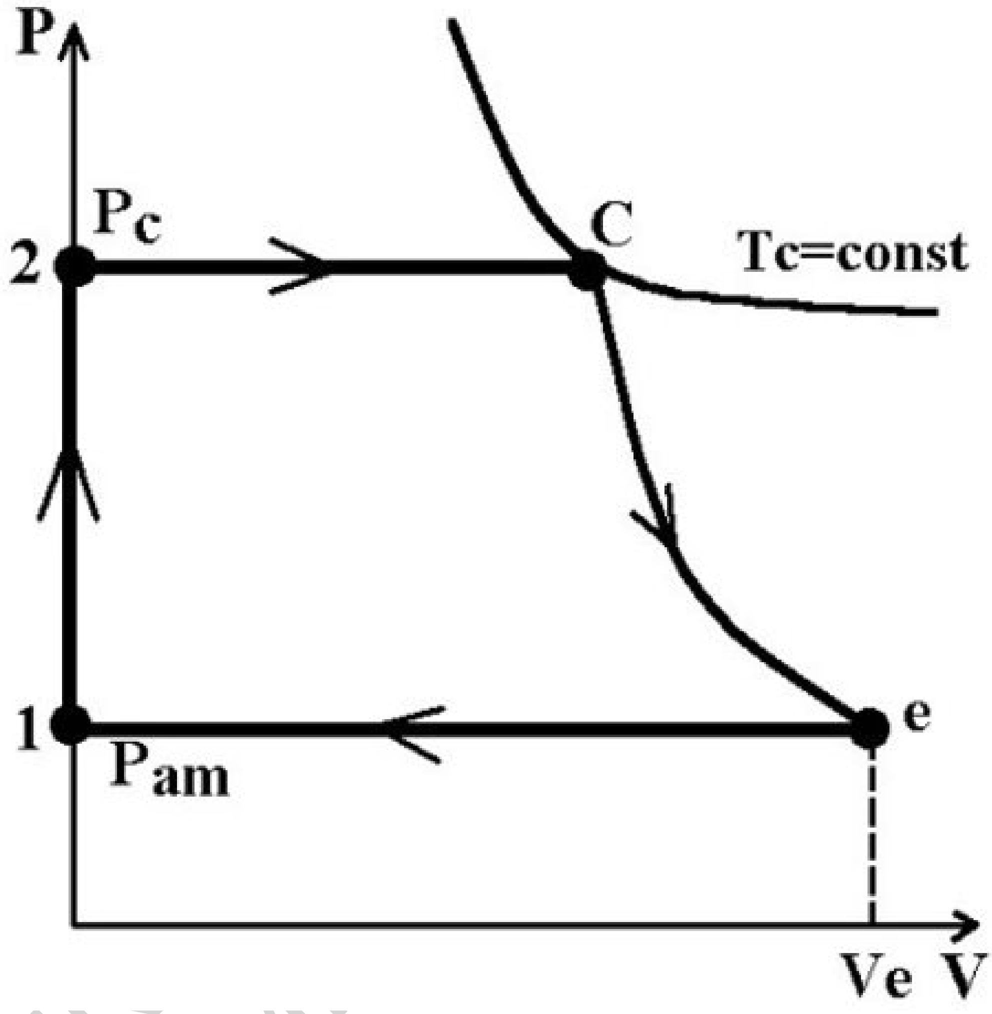

Figure 1 The ideal thermodynamic cycle presented on “p-V” coordinates

Compression process, line "1 - 2", for the liquid rocket engine (LRE) takes place outside of the combustion chamber, i.e. in the pumps or propellant tanks. During compression, the working agent is in the liquid state. The work of compression is negligible in comparison to the work of expansion. Therefore, under the examination of the cycle the compression work is not taken into consideration. In the case of the solid propellant rocket engine (SPRE) the initial state of solid propellant corresponds to point 1 and its specific volume V_1 , temperature T_1 and enthalpy $J_1 = c_pT_1$ versus the same parameters of the working agent at the point C are negligibly low, i.e. to be assumed zero.

Proceeding from that, the initial state of the propellant is at the point 1 under V_1 and $p_1 = p_{am}$,where p_{am} is the ambient pressure. The line "2 - C" presents the process into the combustion chamber. This process is characterized by the heat input under the constant combustion chamber pressure and corresponds to the propellant burning into the isobaric combustion chamber where the gas velocity is negligibly low, $W_c \sim 0$. This condition is realized if the ratio of the combustion chamber cross section area F_c to the nozzle throat area F_{th} for cylindrical chamber is $F_c / F_{th} > 3.0$. The combustion process gets complete at the point "C", lying on the T_c isotherm, where T_c is the temperature of the propellant combustion products corresponding to the gas state at the combustion chamber end. The line "C-e" corresponds to the gas expansion in the chamber nozzle during its discharge. In the ideal cycle, this process is assumed as isentropic one. The point "e" determines a gas state at the nozzle exit, and it is considered that $p_e = p_{am}$, i.e. the nozzle operates at the design regime. In the case if p_c / p_{am} is over the critical ratio:

$$p_e \big/ p_{am} > \left[2/(n-1) \right]^{n/(n-1)} \tag{1}$$

then p_e is only determined by the geometrical expansion ratio of the nozzle F_e / F_{th} and the combustion chamber pressure value, where n is the exponent of the expansion process and F_e is the nozzle exit area.

In this case, the pressure p_e and p_{am} can be different corresponding to $p_e > p_{am}$ or $p_e < p_{am}$ in dependence on the nozzle expansion ratio. Under the nozzle operation with uncompleted expansion regime $p_e > p_{am}$ or over-completed expansion regime $p_e < p_{am}$, the cycle shape does not change. In the latter case this takes place under the condition of the flow break away the wall absence into the nozzle ($p_e \geq 0.4\, p_{am}$).

In all cases, the gas expansion work into the nozzle between p_c and p_e is accumulated into the working agent as its kinetic energy. Following energy transitions happens outside of the engine into the environment and they do not influence on the expansion work value. Consequently, in the rocket engine cycle, the expansion work is dependent on the nozzle exit pressure p_e and not dependent on the environmental pressure p_{am}.

This means that the cycle work of the ideal rocket engine with the constant nozzle is invariable to the moment of the normal gas flow break due to the shock input into the nozzle ($p_e \geq p_{am}$).

The line "e - l" closes the cycle and determines a process while the working agent with p_e, V_e parameters can come back into the point 1. Here, a gas must be condensed, i.e. the process passes through a heat extraction under constant pressure. In the real engine, this process is absent and it is introduced into "p - V" diagram in order to close the cycle.

So, the rocket engine ideal cycle under $p_e = p_{am}$ is formed in the "p-V" diagram by an isochor $V_1 = 0$, two isobars with p_c = const and p_{am} = const and the isentrop. The heat input in the cycle is $Q_1 = J_c = C_p T_c$ where J_c is the combustion products constant-pressure (CP) enthalpy at the end of the combustion chamber. The cycle parameters are specified to one kilogram of the working agent. Then $Q_1 = H_p$, where H_p is the burning heat of one kilogram of the propellant. The heat extraction from the cycle is $Q_2 = J_e = C_p T_e$ where J_e is CP enthalpy at the nozzle exit. Such cycle expansion work L_c is equal to the integral of $V \times dp$ .It corresponds to "1 - 2 - C - e - 1" area in the "p -V" diagram coordinates and is determined by the formula

$$L_c = n_{ise} \Big/ \left(n_{ise} - 1\right) \times R \times T_c \times \left[1 - \left(p_e / p_c\right)^{\left(n_{ise}-1\right)/n_{ise}}\right] \qquad (2)$$

or

$$L_c = c_p T_c \times \left[1 - \left(p_e / p_c\right)^{\left(n_{ise}-1\right)/n_{ise}}\right] \qquad (3)$$

where R, c_p and T_c are constant-pressure gas constant, heat capacity and temperature into the combustion chamber, n_{ise} is the isentropic exponent. The cycle work increases as the values of RT_c and the expansion ratio p_c / p_e get larger.
If the gas pressure at the nozzle exit is not equal to the ambient pressure p_{am} ,the cycle shape does not change. Figure 2 shows the engine cycle under the condition of $p_e > p_{am}$. Such engine operates with uncompleted gas expansion into the nozzle. In this cycle the "e - 3" line corresponds to the gas expansion process in the nozzle from p_e to p_{am}. The diagram area of a given cycle and, consequently, its work is less than for the cycle under $p_e = p_{am}$.

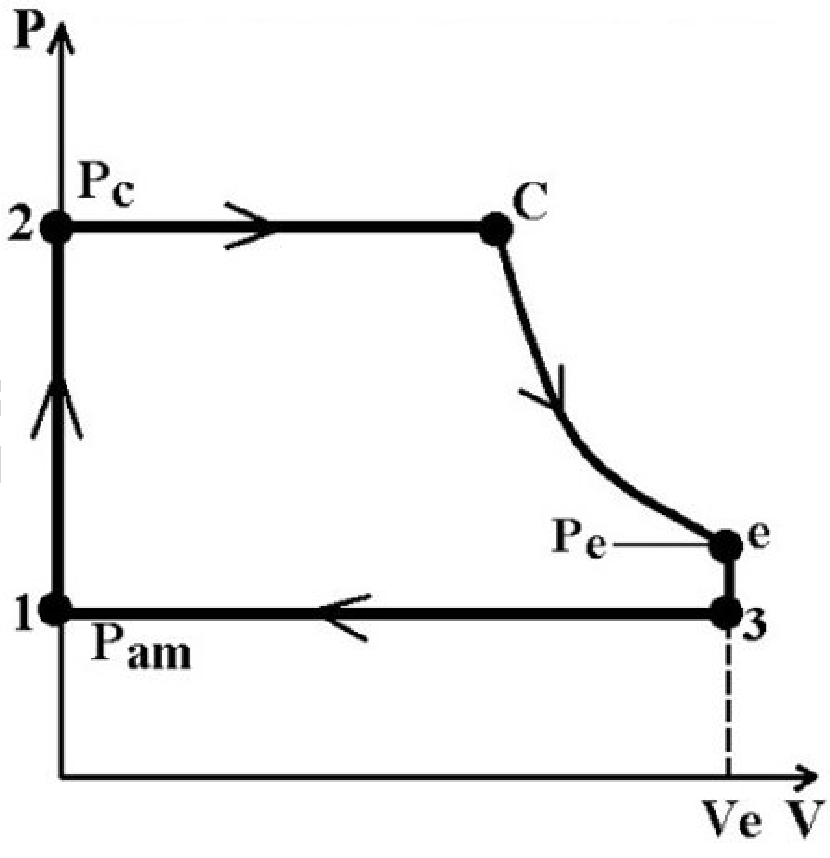

Figure 2 The cycle of the engine under condition $p_e > p_{am}$

The cycle of the engine operating on over-complete regime, i.e. under $p_e < p_{am}$ is represented in Figure 3. In this case, the section "e - 3 - 4" is added to the cycle with $p_e = p_{am}$ and the work corresponding to this section area has the opposite sign to the work of the basic cycle part "1 - 2 - C - e - 1" because processes in "e - 3 - 4" section pass in other direction. Here, the complete area determining the useful cycle work under $p_e < p_{am}$ is decreased versus to the cycle under $p_e = p_{am}$.

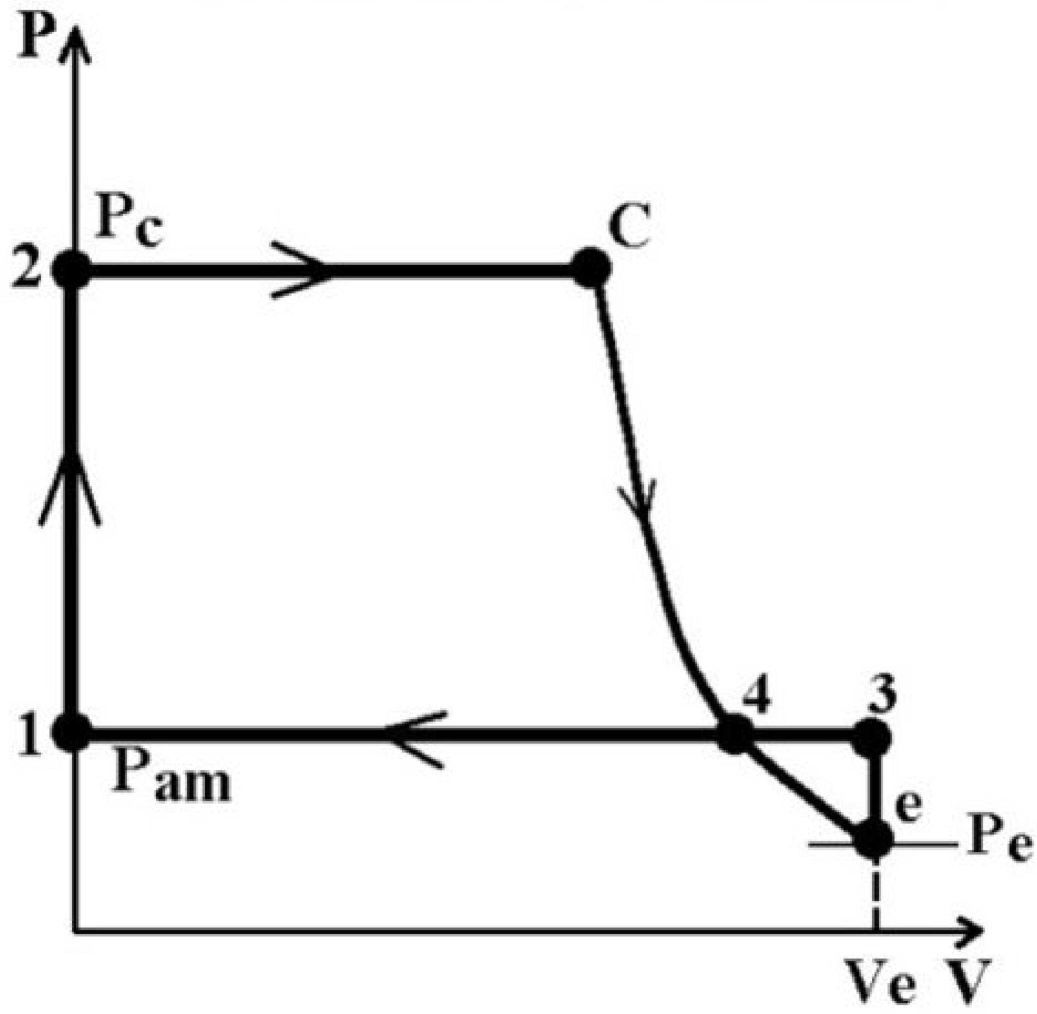

Figure 3 The cycle of the engine under condition $p_c < p_{am}$

The conclusion is that the cycle work is the utmost when the gas pressure at the nozzle exit is equal to the ambient pressure. Obviously, complete thermal energy cannot be fully transformed into mechanical work of the cycle. The energy dissipation and the limited range of the expansion ratio between the combustion chamber pressure p_c and some value of the nozzle exit pressure p_e prevent this process.

Generally, in the iso-energetical flow working agents have always thermal or chemical energy that is not transformed into mechanical work of the cycle. That is why the conception of the thermal efficiency η_t has been introduced.

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Bibliography

[1] Vasiliev A.P., Kudryavtsev V.M, Kuznetsov V.A et al (1993) Fundamentals of rocket engines theory and calculations. Book 1 and 2, 383 and 384 pp., Moscow, Russia, Vystshaya Shola [This contains thermodynamic fundamentals of operating process in LRE chamber, the thrust theory, specific impulse, combustion process and combustion products dischanrge calculations, theory and calculation of different nozzles etc.]

[2] Arkharov A.M., Isayev S.I., et al., (1986) Thermaltechnique, 432 pp., Moscow, Machinoastrojenie, Russia [in Russian], [This presents the basic data on the heat engine systems for the different applications].

[3] Haywood R.W. (1975), Analysis of engineering cycles, 280 pp., Pergamon Press, [in Russian, 1979, Energy], [This presents the basic data on the heat and refrigerating units].

[4] Sutton G.P., Ross D.M. (1976),Rocket Propoulsion elements, 327 pp.,Wiley [This presents the introduction to the engineering of rockets].

Biographical Sketches

Vladimir M. Polyaev born in 1925, graduated from the Moscow Aviation Institute in 1948. He took his Ph.D. degree in 1961 and became D.Sc. (Eng) in 1973. He is the author of more than 200 publications in the field of constructions and characteristics of rocket engines of different applications. Research interests are concerned on energy-machine-building, concretely in the sphere of constructions and characteristics of engines, thermodynamic fundamentals of operating process, the thrust theory, combustion process and combustion products discharge calculations, theory and calculation of different nozzles etc.

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