THERMODYNAMIC CYCLES OF DIRECT AND PULSED-PROPULSION ENGINES

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Contents

Summary

This chapter considers engines with intermittent cycles and cycles of pulsejet engines. These include, piston engines of various designs, pulsejet engines, and gas-turbine propulsion systems with fuel combustion at a constant volume. This chapter presents thermodynamic cycles of thermal engines in which the propulsive mass is a mixture of air and either a gaseous fuel or vapor of a liquid fuel (on the initial portion of the cycle), and gaseous combustion products (over the rest of the cycle).

1. Cycles of Piston Engines of Internal Combustion.

Piston engines of internal combustion are utilized in motor vehicles, aircraft, ships and boats, and locomotives. They are also used in stationary low-power electric generators. Given the variety of conditions that engines of internal combustion should meet, depending on their functions, engines of various types have been designed. From the standpoint of thermodynamics, however, i.e. in terms of operating cycles of these engines, all of them can be classified into three groups: (a) engines using cycles with heat addition at a constant volume (V = const); (b) engines using cycles with heat addition at a constant pressure (p = const); and (c) engines using the so-called mixed cycles, in which heat is added at either a constant volume or a constant pressure.

Cycle with heat addition at a constant volume. Engines using the cycle in which heat is added at V=const consume liquid or gaseous fuels (gasoline, kerosene, generator and lighting gas, etc.). The cycle with heat addition at a constant volume is analyzed most easily with the example of the so-called four-stroke engine, whose schematic drawing and pV-diagram are shown in Fig. 1.

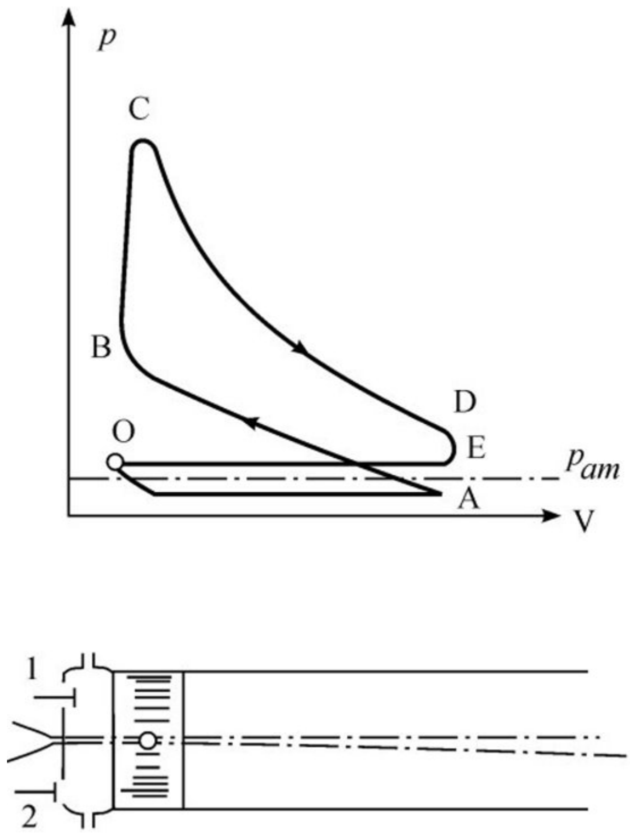

Figure 1: *PV*-diagram of a four-stroke engine

When the piston moves to the right (first stroke), its cylinder sucks in through the inlet valve (in internal combustion engines, valves are driven by a special mechanism) the propellant, which is either a mixture of a combustible gas and air, or a mixture of vapor and microscopic droplets of fuel with air. The suction process corresponds to the line OA in the *pV*-diagram. When the piston moves to the left, and its inlet and outlet valves are closed (the second stroke), the propulsive mixture is pressed, which corresponds to the line AB in the *pV*-diagram (Fig.1) $v_2 = v_1 \varepsilon^{-1}/\rho$. At the moment when the piston arrives at its extreme left position, the propulsive mass is ignited by an electric spark. The rapid pressure build-up due to combustion of the fuel mixture concurrent with an insignificant piston displacement is shown by the line BC. The subsequent expansion of combustion products and concurrent piston motion to the right is called the working stroke (third stroke) because work is done by the engine on this portion of the cycle. This process corresponds to the line CD in the *pV*-diagram. When the piston arrives at its extreme right position, the exhaust valve 2 is opened and, because the gas freely flows into the atmosphere, the pressure in the cylinder drops rapidly (the line DE in the *pV*-diagram). The fourth stroke proceeds with the open exhaust valve and results in ejection or exhaust of gases remaining in the cylinder, whose pressure is just slightly higher than the atmospheric pressure. The fourth stroke is presented in the diagram by the line EO. The exhaust process is followed by a new suction stroke, and in this manner the engine is operated continuously. The lines of suction and exhaust in the diagram do not reflect real processes of changes in the propulsive mass, so they are not considered in the analysis of the thermodynamic cycle. In the idealized cycle, both the suction and exhaust in the engine should proceed at the constant (atmospheric) pressure, therefore the works done during these strokes are equal in absolute value and have opposite signs, hence the total work done during these two strokes is zero. The processes of compression and expansion of the propulsive mass, in which a fraction of energy is lost and some heat is imparted to cylinder walls, are approximately described by reversible adiabatic processes in the theoretical analysis of the engine cycle. The combustion process, in which the propulsive mass transforms to combustion products, is treated as a reversible heat addition to an unchanged propulsive mass. In this approximation, the combustion process is assumed to be instantaneous, i.e. the total quantity of heat is added so fast that the piston does not displace notably in the process, consequently the volume is constant. The process of pressure drop in the cylinder when the exhaust is let out into the atmosphere (the line DE in the diagram) is approximated by an equivalent isochoric process 4—1 (Fig. 2) since the work done during the exhaust stroke is zero, consequently, the total internal energy of the propulsive mass and environment, $U + U'$, does not change, i.e. $U + U = U + U$. But the increment of the internal energy of the environment, $U - U$, is the quantity of the supplied heat Q, moreover, since $U + U =$ const and $Q = U - U$, the process of exhaust and isochoric cooling of the propulsive mass are equivalent. It follows from the above reasoning that the cycle with heat addition at V = const is presented in the *pV*- and *TS*-diagrams shown in Figs. 2 and 3.

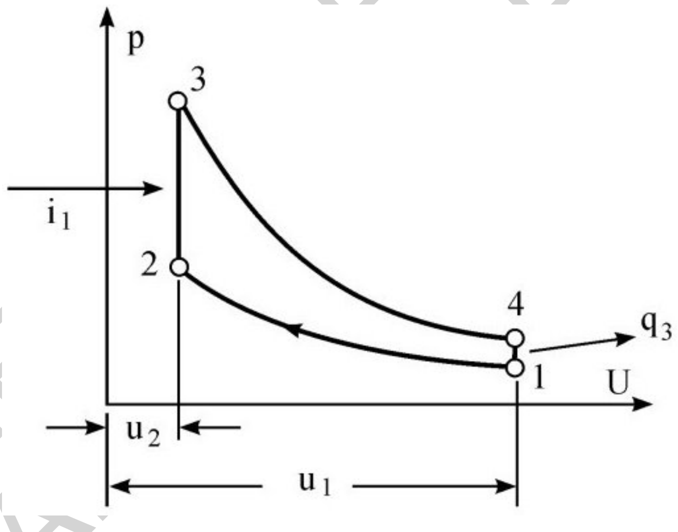

Figure 2: Approximated *PV*-diagram of four-stroke engine

Here 1—2 corresponds to the adiabatic compression of the combusting mixture; 2—3 represents the adiabatic heat addition (due to fuel combustion); 3—4 corresponds to the adiabatic expansion of combustion products; 4—1 represents the conditional isochoric process of heat rejection equivalent to the ejection of exhaust gases. The ratio between volumes $V_1 : V_2$ is denoted by ε and is termed the degree of compression. The ratio between pressures $p_3 : p_2$ is denoted by λ and is termed the degree of pressure build-up. A cycle with heat addition at V = const is controlled by the initial state of the propulsive mass, whose parameters are assumed to be known at point 1, alongside the degrees of compression ε, and pressure build-up, λ. If the propulsive mass in the engine consists of an ideal gas, whose specific heat c_v is constant, the propulsive mass parameters at all cardinal points of the cycle (points 1, 2, 3, and 4) are given by the following formulas:

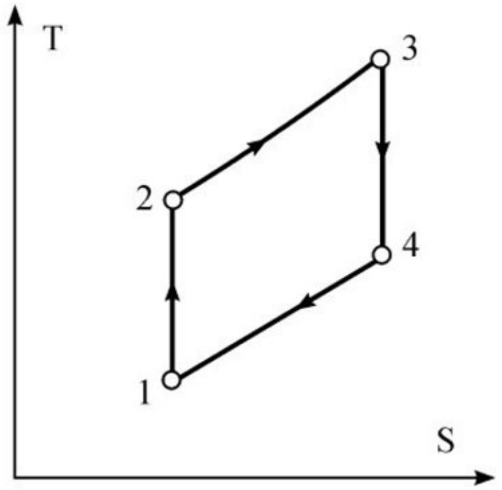

Figure 3: Approximated *TS*-diagram of four-stroke engine

At point 2:

$$V_2 = V_1\ \varepsilon^{-1};\ P_2 = P_1(V_1V_2^{-1})^k = P_1\ \varepsilon^k;\ T_2 = T_1(V_1V_2^{-1})^{k-1} = T_1\ \varepsilon^{k-1}.$$

At point 3:

$$V_3 = V_2 = V_1V_2^{-1};\ P_3 = P_2\lambda\ = P_1\ \varepsilon^k\lambda\ ;\ T_3 = T_\lambda\lambda\quad . \qquad (1.1.1)$$

At point 4:

$$V_4 = V_1;\ P_4 = P_3(V_3V_4^{-1})^k = P_3(V_2V_1^{-1})^k = P_3(\ \varepsilon^k)^{-1}$$
$$T_4 = T_3(V_3V_4^{-1})^{k-1} = T_3(k-1)^{-1} = T_1\lambda.$$

It follows from the analysis of pV- and *TS*-diagrams that at point 3 the pressure p_3 and temperature t_3 are maximal. The thermodynamic efficiency of the cycle with heat addition at V = const is calculated by the general formula

$$\eta_{\mathrm{t}} = 1 - q_2q_1^{-1},$$

where q_1 and q_2 are respectively the quantities of heat per 1 kg of the propulsive mass added and rejected during the cycle. The heat addition and rejection during the cycle take place at constant volumes, therefore, q_1 and q_2 are equal to the changes in the internal energy on the cycle stages 2—3 and 4—1. If the gas specific heat is constant with temperature, then q_1 and q_2 are given by the formulas $q_1=c_v(T_3-T_2)$; $q_2=c_v(T_4-T_1)$ Hence follows $\eta_t=1-(T_4-T_1)(T_3-T_2)^{-1}$By substituting the temperatures T_2, T_3, and T_4 from

Eq. (1.1.1), we obtain η_t=1-(ε^{k-1})$^{-1}$Cycle with mixed heat addition In 1904 G. V. Trinkler, a Russian engineer, obtained a patent on the invention of a compressor-less high-pressure engine using a cycle with mixed heat addition, see Fig. 4.

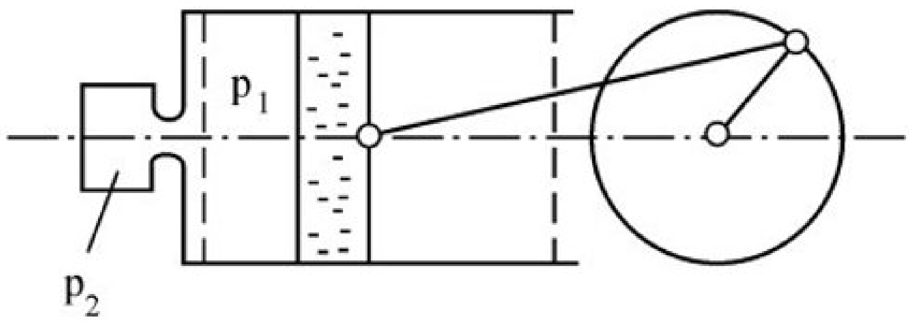

Figure 4: Trinkler's compressor-less high-pressure engine using a cycle with mixed heat addition

In engines with high λ, the temperature T_2 rises to a very high level, higher than the spontaneous ignition temperature of the fuel mixture (see). All modern engines with spontaneous ignition operate to the mixed cycle. In some of these engines fuel is dispersed in a special chamber (the so-called for-chamber) located in the upper section of the engine cylinder and connected to the working volume of the cylinder through one or several narrow channels (Fig. 4). Air is compressed, as in compressor engines, to a high degree of compression to insure the spontaneous ignition of the fuel. When the air is compressed, the pressure p in the cylinder rises faster than in the for-chamber connected to the cylinder through a narrow channel. Owing to the pressure difference, a flow of air is driven from the cylinder into the for-chamber, and this flow is used to disperse liquid fuel injected into the for-chamber. After the first spark, the pressure in the for-chamber becomes higher than in the cylinder. The process of combustion of a fraction of the fuel in the for-chamber is represented in the pV-diagram (Fig. 5) by the isochoric process 2—3 with addition of heat q_1.

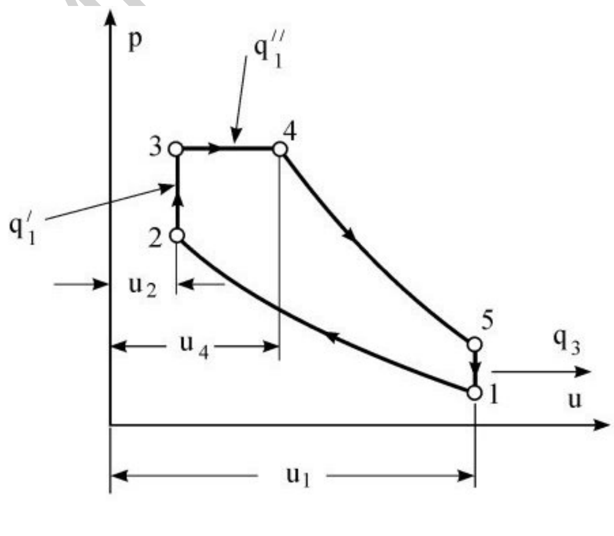

Figure 5: *PV*-diagram of Trinkler engine

Due to the fast pressure build-up in the for-chamber, the flow direction is reversed, and the mixture of hot combustion products, air, and fuel vapor not burnt in the for-chamber, whose temperature is 1500—1800 C, is driven from the for-chamber into the cylinder. This flow has a high velocity and generates a lot of vortices, which results in the thorough mixing of remaining fuel with air.

The result of this process is a homogeneous mixture burnt in the cylinder at a constant pressure. The process of fuel combustion in the cylinder is represented by the isobaric curve 3—4 with the added heat q. Upon the termination of combustion, its products adiabatically expand (process 4—5), and the exhaust gas is let out into the atmosphere (process 5—1). In engines of other types using the mixed cycle, liquid fuel is dispersed through mechanically controlled nozzles.

The fuel is fed to the nozzles by a pump at a high pressure of up to 300—400 atm. Thus, the thermodynamic cycle of the engine using the mixed heat addition approximated by the curve 1—2—3—4—5—1 consists of the following processes:1—2 adiabatic compression of air; 2—3 isochoric heat addition;3—4 isobaric heat addition;4—5 adiabatic expansion of combustion products;5—1 isochoric heat rejection. Gas parameters at points 2, 3, 4, and 5 can be easily calculated, provided that the propulsive mass is an ideal gas, whose heat capacity is constant with temperature:

$$V_2 = V_1\ \varepsilon^{-1};\ P_2 = P_1\ \varepsilon^{k};\ T_2 = T_1\ \varepsilon^{k-1}\ ; V_3 = V_2 = V_1\ \varepsilon^{-1};\ P_3 = P_1\ \varepsilon^{k}\lambda\ ;$$
$$T_3 = T_1\ \varepsilon^{k-1}\lambda\ ;\ V_4 = V_1\rho\varepsilon^{-1};\ P_4 = P_3 = P_1\ \varepsilon^{k}\lambda\ ;\ T_4 = T_1\ \varepsilon^{k-1}\lambda\rho\ ;$$

where, as in the previous sections, ε is the degree of compression, $\varepsilon = V_1/V_2$; λ is the degree of pressure build-up, $\lambda = P_3/P_2$; ρ is the degree of preliminary expansion, $\rho = V_4/V_3$. The quantities of added and rejected heat during the cycle are, respectively,

$$q_1 = c_v\ (T_3 - T_2) + c_p(T_4 - T_3) = \ c_v\ T_1\ \varepsilon^{k-1}[(\lambda - 1) + k\lambda(\rho - 1)]\ ;$$
$$q_2 = c_v(T_5 - T_1) = c_v T_1(\lambda\rho^k - 1).$$

In the mixed cycle, the pressure $p_3 = p_4$ and temperature T_4 are maximal. In Fig. 6 the mixed cycle is shown by curves plotted in coordinates *T—S*. The thermal efficiency of the mixed cycle is

$$\eta = 1 - (\lambda\rho^k - 1)/(\varepsilon^{k-1}[(\lambda - 1) + k\lambda(\rho - 1)])\ . \qquad (1.2.2).$$

This formula shows that the thermal efficiency of the mixed cycle, like the thermal efficiency of the cycles with isochoric and isobaric heat addition, increases with the degree of compression ε, moreover, it depends on λ and ρ. At $\lambda = 1$ the mixed cycle turns to the cycle with isobaric heat addition, and at $\rho = 1$ to the cycle with isochoric heat addition. Theoretically, the work done during the mixed cycle is

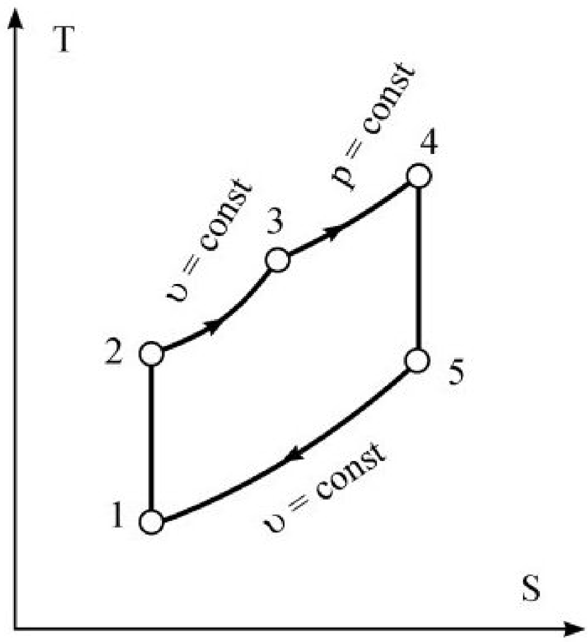

Figure 6: Mixed cycle

$$L = [(V_1 - V_c)P/((\varepsilon - 1)(k - 1))][\lambda(\rho - 1)(k - 1)] + \lambda\rho(1 - 1/(\delta^k - 1)) - (1 - 1/(\varepsilon^{k-1})) \ ,$$

where $\delta = \varepsilon/\rho$ is the degree of adiabatic expansion.

The average indicative pressure is

$$P_i = [P_1/(\varepsilon - 1)(k - 1)][\lambda(\rho - 1)(k - 1) + \lambda(1 - 1/(\delta^k - 1)) - (1 - 1/(\varepsilon^{k-1})) \ .$$

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