

# THERMODYNAMIC CYCLES OF RECIPROCATING AND ROTARY ENGINES

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## Summary

Historical review of the Carnot, Otto, Diesel, Trinkler and Stirling cycles is given and practical realization of these cycles in internal combustion engines is considered.

### 1. The Main Kinds of Reciprocating Engines.

The engines, in which heat generated by combustion of fuel is transformed to mechanical energy, are called the heat (thermal) engines. Heat engines are divided into two main groups: 1. The internal combustion engines having pistons, rotary and combined engines, gas turbines, jet engines etc., i.e. all the engines, in which combustion and generation of heat takes place inside the engine; 2. External combustion engines (steam engines, steam turbines, Stirling engines), which produce mechanical energy due to the heat provided from the outside.

The basic configuration of reciprocating or piston engines includes a cylinder with a piston. Combustion of the fuel takes place inside the cylinder in the environs of an air (oxidizer). So the formation of a combustible mixture can be both inside and outside of the cylinder. Historically the first engine with an external mixing was created in 1876 by a German engineer Nickolaus Augustus Otto (1832-1891). Certainly, there were attempts at creating engines before Otto. One successful attempt was by a French inventor J. Lenoir (1860), but the credit goes to Otto and his engine is known as Otto's engine. In such an engine the main part of air and stream of fuel are mixed up before going to the cylinder. The formation of a fuel-air mixture is complete after entering into the cylinder, where it is compressed by the piston and at the end of the compression process the fuel-air mixture is fired with the help of electrical spark. The products of combustion expand and move the piston, and the mechanical energy so produced in reciprocating motion is transmitted to the shaft through a crank-connecting-rod mechanism as rotary motion. Thus the Otto engine is a piston drive with external mixing and forced ignition. In 1893 another German engineer Rudolf Diesel (1858-1913) created essentially a new type of piston engine known as the Diesel engine. In the Diesel engine the air is compressed by the piston upon entry into the cylinder. The fuel is injected into the compressed air at the end of compression. The fuel-air mixture created inside the cylinder is self ignited due to the high temperature. Thus Diesel engine is an engine with internal mixing and spontaneous combustion. This is the essential difference between the Otto engine and the Diesel engine. The processes of intake, compression, combustion-expansion and exhaust making a full cycle can be carried out in two strokes of the piston (one rotation of the shaft), or in four strokes of the piston (two rotations of the shaft). In the first case the engine is named two-stroke, and in second four-stroke.

## 2. Work Done by a Working Fluid in the Cylinder of a Reciprocating Engine.

Let us consider a closed cylinder with a piston (Figure 1). Gas representing a working fluid takes in the closed volume of the cylinder. After the input of heat ( $q$ ) the gas expands and moves the piston through a distance  $\Delta x = x_2 - x_1$ , i.e. executes mechanical work  $\Delta L = P \cdot x$ , where the force ( $P$ ), acting on the piston is expressed as the product of the pressure ( $p$ ) and area of the piston  $F$ , i.e.  $P = pF$ . Then,  $\Delta L = p \cdot \Delta V$ , where  $\Delta V = F \cdot \Delta x$  is a modification of volume as a result of the gas expansion (Figure 1). Let us introduce the definitions of specific work  $l = \frac{\Delta L}{m}$  and specific volume  $v = \frac{\Delta V}{m}$ , where  $m$  - mass of gas (working fluid). Considering infinitesimal increments gives the differential expression  $dl = p dV$  and specific work executed by the gas in the cylinder, is calculated with the help of integral

$$l = \int_{v_1}^{v_2} p dV . \quad (1)$$

Obviously, since during the compression of the gas by the piston the initial volume  $v_1$  is more than the final  $v_2$ , i.e.  $dV < 0$  and  $dl < 0$ . Thus, the work done by the gas (work of

the expansion) is positive, and the work spent on compressing the gas is negative. In (1) the availability of  $p$  indicates the possibility of doing work; however indication of doing work is the condition  $dV \neq 0$ . Mechanical work has a thermal equivalent. However to express heat by an integral which is similar to (1), has become possible only after introduction, in 1865 (1852?) by a German scientist Clausius, of the entropy concept. Entropy is a physical quantity, the modification of which is an indication of availability of exchange of energy in the form of heat and it is designated by  $S$ . Then by analogy with (1) we have:

$$q = \int_{S_1}^{S_2} T dS, \quad (2)$$

where  $T$  indicates possibility of heat exchange under the condition  $dS \neq 0$ .

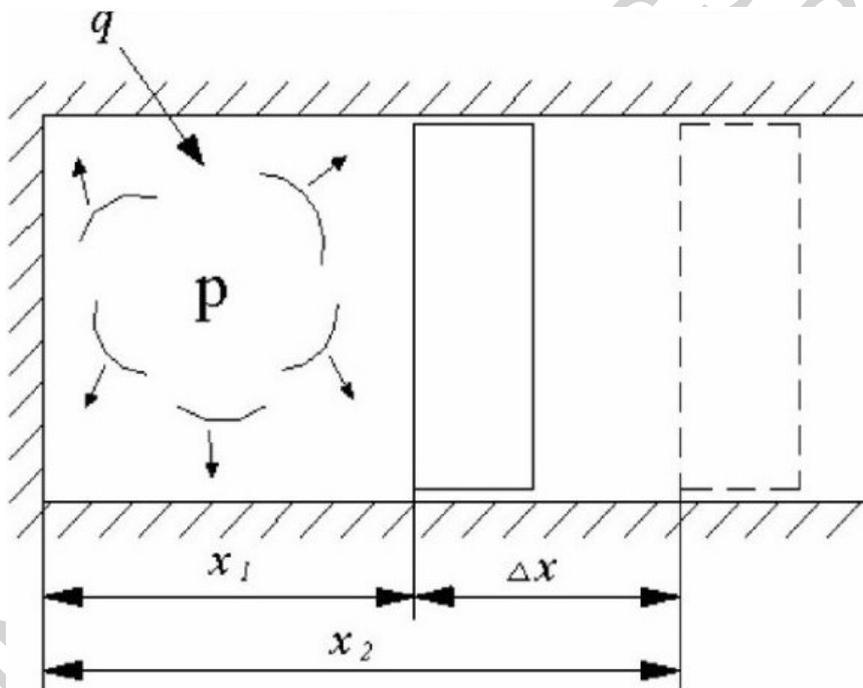


Figure1: The Scheme of the cylinder with the piston for definition of mechanical work

From (1) and (2) it is obvious, that it is possible to represent the processes which are taking place in the cylinder (fig.1), both in coordinates  $V - p$ , and in coordinates  $S - T$ .

As the  $V - p$  diagram expresses mechanical work, it is frequently referred to as the work diagram, and since the diagram  $S - T$  shows thermal variables, it is referred to as the entropy diagram or the thermal diagram.

### 3. Working Process and Indicator Diagram of a Four-stroke Engine.

Figure 2 shows the scheme and indicatory diagram of a four-stroke engine. Indicatory diagram is traditionally the work diagram based on the measurements taken from the working engine or plotted as a result of calculation of in-cylinder processes. Figure 2a

presents gas pressure  $p$  as a function of the cylinder volume  $V$ . It is shown that the indicatory diagram is a closed curve. If the relationship  $p = p(V)$  is converted into  $p = p(\varphi)$ , where  $\varphi$  is the crankshaft rotation angle, using relationship  $V = V(\varphi)$ , which is known from the kinematic analysis, we obtain the developed indicatory diagram. While the piston executes reciprocating motion, its velocity is zero at the points where its direction of motion reverses. These points are known as dead centers. As shown in Figure 2 there are two kinds of such stops: the top and the bottom dead center, or in abbreviated form TDC and BDC respectively. The first stroke is an intake or filling of the cylinder by a fresh charge. In the case of the Otto engine it is a fuel-air mixture, and in the case of the Diesel engine it is air. In the beginning of this stroke the inlet valve 6 is open (outlet valve 7 is closed) and the piston 2 begins moving from TDC to BDC. In the cylinder the pressure drops below pressure  $p_0$  of the environment and becomes equal to  $p_a$  (line ac on Figure 2-b). At the moment of arrival of the piston at the BDC the inlet valve is closed and thus the first stroke is finished. The second stroke - compression, during which the piston 2, moving from BDC to TDC due to closed valves 6 and 7, compresses the working fluid from full volume  $V_a$  up to volume  $V_c$ . The pressure in the cylinder increases from  $p_a$  to  $p_c$  (line ac on Figure 2-b). The third stroke — combustion-expansion takes place while valves 6 and 7 are closed. In case of the Otto engine the ignition of the fuel-air mixture takes place by means of an electric spark. In the case of a diesel engine the fuel injector injects fuel into the compressed air. The resultant fuel-air mixture is spontaneously ignited due the high temperature of the compressed air. As a result of expansion the products of combustion move the piston from TDC to BDC, i.e. the piston makes a power stroke. During combustion, in spite of the fact that the piston moves to BDC and volume is increasing, a sharp compression from  $p_c$  up to  $p_z$  (line cz on Figure 2-b) takes place.  $p_z$  represents the maximum pressure of the cycle. Thereafter there is an expansion of the products of combustion and the pressure drops from  $p_z$  to  $p_b$  (line zb on Figure 2-b). The last, the fourth stroke — is carried out due to transition of the piston from BDC to TDC. At this time the exhaust valve 7 is opened and the piston pushes out the gases, which have filled the cylinder, into the environment with pressure  $p_r$  (line br on Figure 2-b). Obviously,  $p_b > p_0$ . After completion of this action there remain certain amount of the products of combustion, so-called residual gases, in the cylinder which, occupy the volume of compression  $V_c$  (Figure 2-a, b) at pressure  $p_r > p_0$  hinder the next process of filling. However the piston begins to move to BDC and the residual gases expand, their pressure drops up to  $p_{r'} < p_0$  (line rr' on Figure 2-b) and the intake, the first stroke of the next cycle begins. The working process of the four-stroke engine schematically shown on Figure 2-a, is represented as the closed indicator diagram in Figure 2-b. The diagram consists of two main parts: 1. The work obtained in the cylinder, representing the difference of work in the processes of expansion and compression (positive); 2. Work which is spent in gas-changing processes (of the intake and the exhaust) in the cylinder. It is also known as pumping work and as indicated in Figure 2-b, it is negative.

Volume  $V_h$  between TDC and BDC, corresponding to the stroke of the piston is called the working volume. The total volume of the cylinder is  $V_a = V_h + V_c$ . As the

combustion takes place near the TDC, where the volume of the cylinder is not significantly different from  $V_c$ ,  $V_c$  is also frequently called as volume of the combustion chamber. The most important parameter of the working process of a piston engine is the compression ratio

$$\varepsilon = \frac{V_a}{V_c} = 1 + \frac{V_h}{V_c}, \quad (3)$$

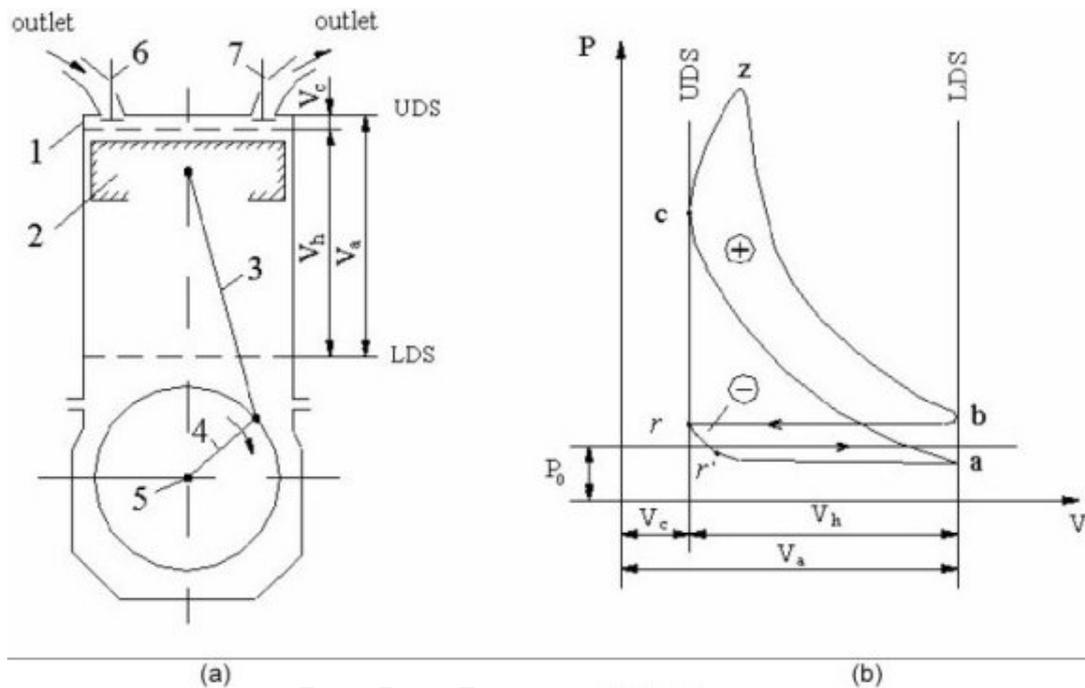


Figure 2: Schematic diagram (a) and indicator diagram (b) of a four-stroke engine. The cylinder, 2-piston, 3-connecting rod, 4-crank, 5-shaft, 6-inlet, 7-outlet valves. The value, 7-outlet valve

According to the above discussion, the compression ratio of Diesel engines is always larger than of Otto engines. It will be clear from the following that the compression ratio influences the performance of a piston engine.

#### 4. Working Process and Indicator Diagram of a Two-stroke Engine.

Figures 3(a) and 3(b) show the schematic of a typical two-stroke Diesel engine and the corresponding indicator diagram respectively. The first stroke of compression and expansion takes place when the piston is at TDC. The exhaust valves 6 and 7 are closed (there are no inlet valves in such scheme!) and the fuel is injected into the compressed air at volume  $V_c$ . The process of combustion (line  $cz$  on Figure 3-b) begins spontaneously and the pressure increases to the maximum value  $p_z$  of the cycle. Next as expansion of the products of combustion takes place, the piston, executing a power stroke, continues to move to BDC and the pressure in the cylinder decreases to  $p_m$  (line  $zm$  on Figure 3-b). The point  $m$  on Figure 3-a corresponds to the moment of opening of the exhaust valves 6 and 7. The pressure continues to drop (line  $mn$  on Figure 3-b) up to

$p_n$ . Coming nearer to BDC the piston opens inlet ports 9, through which air at pressure  $p_k$  from a supercharger 8 enters the cylinder. The air displaces the products of combustion through the outlet valves 6 and 7 while filling the cylinder, i.e. there is a process of forced filling (line na on Figure 3-b), the piston continues to move to BDC, the pressure in the cylinder drops to  $p_a$ . The second stroke begins with the movement (of the piston from BDC). The pressurization-filling proceeds (line ak on Figure 3-b) until the piston blocks the inlet windows. The pressure in the cylinder remains during this period almost constant. At the moment of closing the inlet ports the outlet valves 6 and 7 (point k on Figure 3-b) are also closing and the air compression process begins. The air already had time to displace the products of combustion from the cylinder. Due to compression (line kc on Figure 3-b) the pressure is increased from  $p_k$  to  $p_c$ . So, the working cycle is carried out for two strokes of the piston (one revolution of the shaft). The scheme of forced filling of the two-stroke engine shown on Figure 3a is called the direct (valve-slot-hole) scheme and it is not the only scheme. For example, in two-stroke Otto engines the connecting rod-chamber scheme of gas-charging is used, in which the necessary pressure  $p_k$  forms in the connecting rod chamber, i.e. under the piston, where due to movement towards LDS the fuel-air mixture is compressed. As the inlet ports open this mixture flows into the cylinder, purges and fills it. In such a scheme the supercharger is not driven by the engine as shown for example in Figure 3-a. In two-stroke engines the actual volume  $V_h$  and the geometrical volume  $V_{h'}$  are different. Since  $V_h = V_{h'} - V_n$ , where  $V_n$  corresponds to the volume occupied by the inlet ports (Figure 3-a, b) and is known as volume loss (on this plot there is no useful stroke of the piston!). Accordingly there are actual  $\varepsilon$  and geometric  $\varepsilon'$  ratios of compression, the former is calculated by (3), and the latter by

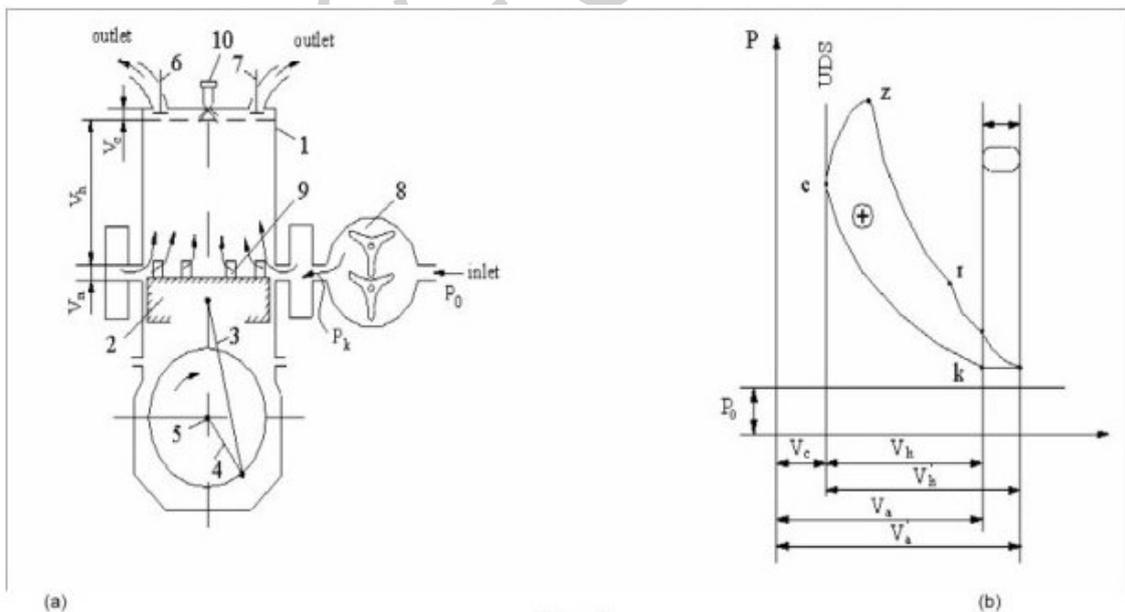


Figure 3: Schematic diagram (a) and indicator diagram (b) two stroked engine. The 1-cylinder, 2-piston, 3- connecting rod, 4-crank, 5-shaft, 6 and 7-outlet valves, 8- supercharger, 9-inlet windows, 10- injector

$$\varepsilon = \frac{\overset{\text{def}}{V'_a}}{V_c} = 1 + \frac{V'_h}{V_c}. \quad (4)$$

and  $\varepsilon' = \frac{\varepsilon - \Psi}{1 - \Psi}$ , where the fraction of the lost volume  $\Psi = \frac{\overset{\text{def}}{V_n}}{V'_h}$  varies from 0.1 to 0.35 in the various engines.

## 5. Main Concepts of Thermodynamics.

The modification of the condition of a thermodynamic system characterized by changing of certain parameters, is called a thermodynamic process. The thermodynamic cycle is a continuous sequence of thermodynamic processes, in which the working fluid returns to its initial condition. Obviously, thermodynamic cycles are represented by closed curves, as the total modification of any thermodynamic parameter of a working fluid in a cycle is equal to zero, i.e.

$\oint dp = 0, \oint dv = 0, \oint dT = 0, \oint di = 0, \oint ds = 0, \oint du = 0$ . In each thermodynamic process the parameters vary in both directions. The change of parameters takes place according to the process law. Some parameters may not change. The thermodynamic processes: isobaric, isohoric, isothermal processes correspond respectively to the conditions:  $p = \text{const}$ ,  $v = \text{const}$ ,  $T = \text{const}$ . Adiabatic process is a process, in which there is no heat exchange between a system and environment; isotropic and isenthalpic processes take place at constant entropy and enthalpy and therefore, adiabatic process is an isentropic process. The adiabatic process is described by the relation  $pv^k = \text{const}$ , where the isentropic exponent  $k = \frac{c_p}{c_v}$  is the ratio of specific heat at constant pressure to that at

constant volume. It is constant for a given working fluid, for example for air  $k = 1.4$ . The thermodynamic process described by  $pv^n = \text{const}$ , is said to be polytropic. The polytropic exponent is a constant. In a thermodynamic cycle always there are compression processes and expansion processes of a working fluid, and also processes with add ( $dq > 0$ ) and remove ( $dq < 0$ ) heat. According to a thermodynamic cycle thermal energy is converted into mechanical energy and vice versa. According to the second law of a thermodynamics for fulfillment of a thermodynamic cycle the availability of two sources of heat with different temperatures is necessary; one hot and the other cold. A thermodynamic cycle in which greater amount of heat is associated with a working fluid at a higher temperature and smaller amount of heat is associated with lower temperature, is named direct. The difference between these heats is equal to work, accomplished in a cycle. The cycle is reversible, if to a working fluid with smaller amount of a heat at lower temperature greater amount of heat at higher temperature is passed. The difference between these heats is equal to the spent work. Thermodynamic process, in which thermodynamic system and environment, interacting with it return to initial conditions without any residual modifications, is named reversible. Otherwise process is irreversible. If all processes in a cycle are reversible, then the cycle is also reversible. For a cycle to be irreversible, the irreversibility even of one process in it is sufficient. The direct thermodynamic cycles are characterized by thermal efficiency of a

cycle representing the ratio of work, done in a direct reversible thermodynamic cycle, to the heat fed into the working fluid from external sources. Similarly, the ratio of the heat removed in a reverse thermodynamic cycle from a cooled system, to the spent work in this cycle, is known as refrigerating factor. An example of a reversible thermodynamic cycle is the cycle the Carnot.

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### Biographical Sketch

**Revaz Kavtaradze** (b. 1951) graduated from Georgian Polytechnic University (Tbilisi, Georgia) in 1973. He holds a D.Sc. (Engineering) degree in Internal Combustion Engine design from Bauman Moscow Technical University. Currently he is a professor at the Internal Combustion Engines department of BMSTU. Mr. Kavtaradze lectured broadly and carried out R&D programs worldwide (Technical University of Munich (Germany), Rostock University (Germany), Beijing University of Technology (China)). He has extensive experience and particular interest in the field of Internal Combustion Engines working processes and heat transfer. He is an author of numerous monographs and scientific papers.