Lecture 9
DUAL CYCLE

INTERNAL COMBUSTION ENGINES

By

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3.1.3 DUAL CYCLE

If Eqs. (3-31) and (3-77) are compared, it can be seen that to have the best of both worlds, an engine ideally would be compression ignition but would operate on the Otto cycle. Compression ignition would operate on the more efficient higher compression ratios, while constant-volume combustion of the Otto cycle would give higher efficiency for a given compression ratio.

The modern high-speed CI engine accomplishes this in part by a simple operating change from early diesel engines. Instead of injecting the fuel late in the compression stroke near TDC, as was done in early engines, modern CI engines start to inject the fuel much earlier in the cycle, somewhere around 20° bTDC. The first fuel then ignites late in the compression stroke, and some of the combustion occurs almost at constant volume at TDC, much like the Otto cycle. The resulting cycle shown in Fig. 3-9 is a cross between an SI engine cycle and the early CI cycles. The air-standard cycle used to analyze this modern CI engine cycle is called a **Dual cycle,** or sometimes a **Limited Pressure cycle**(Fig. 3-10***). It is a dual cycle because the heat input process of combustion can best be approximated by a dual process of constant volume followed by constant pressure.*** It can also be considered a modified Otto cycle with a limited upper pressure.

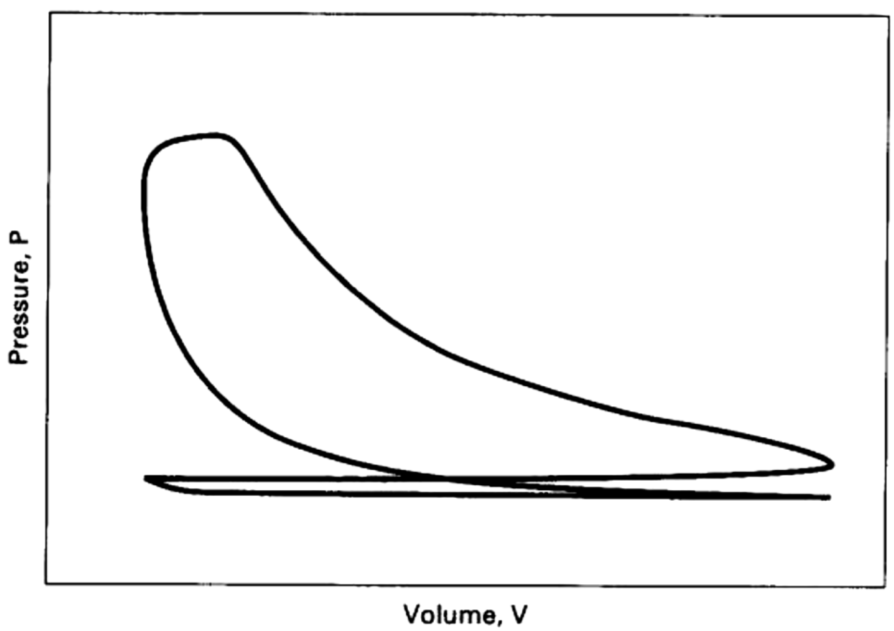

Figure 3-9 Indicator diagram of a modern CI engine operating on a four-stroke cycle.

Thermodynamic Analysis of Air-Standard Dual Cycle

The analysis of an air-standard Dual cycle is the same as that of the Diesel cycle except for the heat input process (combustion) *2-x-3*.

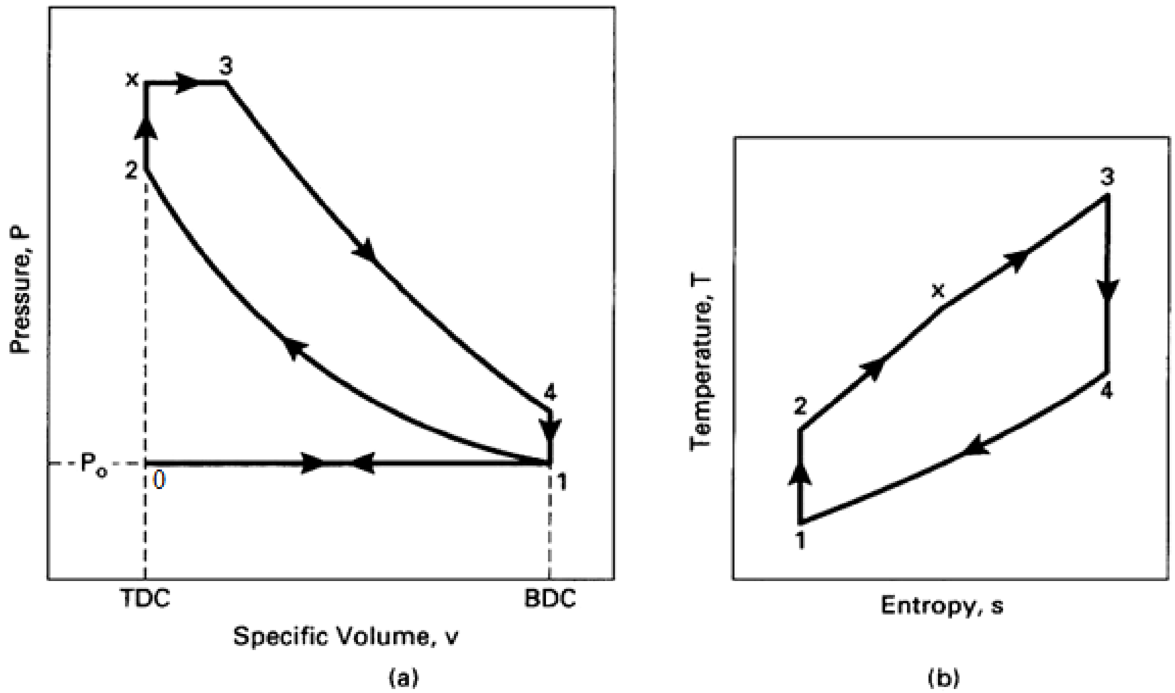

Figure 3-10 Air-standard Dual cycle, 0-1-2-X-3-4-1-0 , which approximates the four-stroke cycle of a modern CI engine on **(a)** pressure-specific volume coordinates, and **(b)** temperature-entropy coordinates.

Process 0-1—constant-pressure intake of air at P_o.
Intake valve open and exhaust valve closed:

$$w_{0\text{-}1} = P_o(v_1 - v_o)$$

Process 1-2—isentropic compression stroke.
All valves closed:

$$T_2 = T_1(v_1/v_2)^{k-1} = T_1(V_1/V_2)^{k-1} = T_1(r_c)^{k-1}$$

$$P_2 = P_1(v_1/v_2)^k = P_1(V_1/V_2)^k = P_1(r_c)^k$$

$$V_2 = V_{TDC}$$

$$q_{1-2} = 0$$

$$w_{1-2} = (P_2 v_2 - P_1 v_1)/(1-k) = R(T_2 - T_1)/(1-k)$$

$$= (u_1 - u_2) = c_v(T_1 - T_2)$$

Process 2-x—constant-volume heat input (first part of combustion).
All valves closed:

$$V_x = V_2 = V_{TDC}$$
$$w_{2-x} = 0$$
$$Q_{2-x} = m_m c_v(T_x - T_2) = (m_a + m_f)c_v(T_x - T_2)$$
$$q_{2-x} = c_v(T_x - T_2) = (u_x - u_2)$$
$$P_x = P_{max} = P_2(T_x/T_2) \tag{3-78}$$

Pressure ratio is defined as the rise in pressure during combustion, given as a ratio:

$$\alpha = P_x/P_2 = P_3/P_2 = T_x/T_2 = (1/r_c)^k(P_3/P_1) \tag{3-79}$$

Process x-3—constant-pressure heat input (second part of combustion).
All valves closed:

$$P_3 = P_x = P_{max} \tag{3-80}$$
$$Q_{x-3} = m_m c_p(T_3 - T_x) = (m_a + m_f)c_p(T_3 - T_x) \tag{3-81}$$
$$q_{x-3} = c_p(T_3 - T_x) = (h_3 - h_x) \tag{3-82}$$
$$w_{x-3} = q_{x-3} - (u_3 - u_x) = P_x(v_3 - v_x) = P_3(v_3 - v_x) \tag{3-83}$$
$$T_3 = T_{max} \tag{3-84}$$

Cutoff ratio:

$$\beta = v_3/v_x = v_3/v_2 = V_3/V_2 = T_3/T_x \tag{3-85}$$

Heat in:

$$Q_{in} = Q_{2-x} + Q_{x-3} = m_f Q_{HV}\eta_c \tag{3-86}$$
$$q_{in} = q_{2-x} + q_{x-3} = (u_x - u_2) + (h_3 - h_x) \tag{3-87}$$

Process 3-4—isentropic power or expansion stroke.
All valves closed:

$$q_{3-4} = 0$$
$$T_4 = T_3(v_3/v_4)^{k-1} = T_3(V_3/V_4)^{k-1}$$
$$P_4 = P_3(v_3/v_4)^k = P_3(V_3/V_4)^k$$
$$w_{3-4} = (P_4v_4 - P_3v_3)/(1-k) = R(T_4 - T_3)/(1-k)$$
$$= (u_3 - u_4) = c_v(T_3 - T_4)$$

Process 4-1—constant-volume heat rejection (exhaust blowdown).
Exhaust valve open and intake valve closed:

$$v_4 = v_1 = v_{BDC}$$

$$w_{4-1} = 0$$

$$Q_{4-1} = Q_{out} = m_m c_v (T_4 - T_1) = m_m c_v (T_4 - T_1)$$

$$q_{4-1} = q_{out} = c_v (T_4 - T_1) = (u_4 - u_1)$$

Process 0-1—constant-pressure exhaust stroke at P_o.
Exhaust valve open and intake valve closed:

$$w_{1-0} = P_o(v_0 - v_1) = P_o(v_0 - v_1)$$

The thermal efficiency of Dual cycle:

$$(\eta_t)_{Dual} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \qquad (3.88)$$

$$= 1 - \frac{c_v(T_4 - T_1)}{[c_v(T_x - T_2)] + [c_p(T_3 - T_x)]}$$

$$= 1 - \frac{(T_4 - T_1)}{[(T_x - T_2)] + [k(T_3 - T_x)]}$$

$$v_x = v_2, \qquad \frac{P_x}{P_2} = \alpha = \frac{T_x}{T_2} \rightarrow \quad \boldsymbol{T_2 = \frac{T_x}{\alpha}} \qquad (3-89)$$

$$P_x = P_3, \qquad \frac{v_3}{v_x} = \beta = \frac{T_3}{T_x} \rightarrow \quad \boldsymbol{T_3 = T_x\,\beta} \qquad (3-90)$$

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \left(\frac{v_x\beta}{v_1}\right)^{k-1}\left(\frac{v_2\beta}{v_1}\right)^{k-1} = \left(\frac{\beta}{r_c}\right)^{k-1} \rightarrow T_4 = T_3\left(\frac{\beta}{r_c}\right)^{k-1}$$

$$by\ subtituting\ in\ eq.(3-90) \quad \boldsymbol{T}_4 = \boldsymbol{T_x}\frac{\boldsymbol{\beta}^{\mathbf{k}}}{(\mathbf{r_c})^{\mathbf{k-1}}} \qquad (3-91)$$

$$\frac{T_2}{T_1} = (\mathrm{r_c})^{\mathrm{k-1}} \rightarrow T_1 = \frac{T_2}{(\mathrm{r_c})^{\mathrm{k-1}}} \rightarrow \boldsymbol{T_1} = \frac{\boldsymbol{T_x}}{\boldsymbol{\alpha}\,(\mathbf{r_c})^{\mathbf{k-1}}} \qquad (3-92)$$

By subtituting eqs. (3-89),(3-90),(3-91),(3-92) in eq. (3-88) we get:

$$(\eta_t)_{Dual} = 1 - \frac{\boldsymbol{T_x}\frac{\boldsymbol{\beta}^{\mathbf{k}}}{(\mathbf{r_c})^{\mathbf{k-1}}} - \frac{\boldsymbol{T_x}}{\boldsymbol{\alpha}\,(\mathbf{r_c})^{\mathbf{k-1}}}}{\left[\left(T_x - \frac{T_x}{\alpha}\right)\right] + [k(T_x\,\beta - T_x)]}$$

$$= 1 - \frac{\frac{\mathbf{1}}{(\mathbf{r_c})^{\mathbf{k-1}}}\,T_x(\beta^k - \frac{\mathbf{1}}{\boldsymbol{\alpha}})}{T_x\left[\left(1 - \frac{1}{\alpha}\right) + [k(\beta - 1)]\right]}$$

$$\therefore \quad (\eta_t)_{Dual} = 1 - \frac{1}{(\mathbf{r_c})^{\mathbf{k-1}}}\left[\frac{(\boldsymbol{\alpha}\,\beta^k - \mathbf{1})}{(\alpha - 1) + [\alpha k(\beta - 1)]}\right] \qquad (3-93)$$

EXAMPLE PROBLEM 3-2

A small truck has a four-cylinder, four-liter CI engine that operates on the air-standard Dual cycle (Fig. 3-10) using light diesel fuel at an air-fuel ratio of 18. The compression ratio of the engine is 16:1 and the cylinder bore diameter is 10.0 cm. At the start of the compression stroke, conditions in the cylinders are 60°C and 100 KPa with a 2% exhaust residual. It can be assumed that half of the heat input from combustion is added at constant volume and half at constant pressure.
Calculate:

1. temperature and pressure at each state of the cycle
2. indicated thermal efficiency
3. engine volumetric efficiency

Solution:

For one cylinder:

$$V_d = (4\ \text{L})/4 = 1\ \text{L} = 0.001\ \text{m}^3 = 1000\ \text{cm}^3$$

Using Eq. (2-12):

$$r_c = V_{BDC}/V_{TDC} = (V_d + V_c)/V_c = 16 = (1000 + V_c)/V_c$$
$$V_c = 66.7\ \text{cm}^3 = 0.0667\ \text{L} = 0.0000667\ \text{m}^3$$

Using Eq. (2-8):

$$V_d = (\pi/4)B^2S = 0.001\ \text{m}^3 = (\pi/4)(0.10\ \text{m})^2S$$
$$S = 0.127\ \text{m} = 12.7\ \text{cm}$$

State 1:

$\underline{T_1 = 60°\text{C} = 333\ \text{K}}$ given in problem statement

$\underline{P_1 = 100\ \text{kPa}}$ given

$V_1 = V_{BDC} = V_d + V_c = 0.001 + 0.0000667 \underline{= 0.0010667\ \text{m}^3}$

Mass of gas in one cylinder at start of compression:

$$m_m = P_1V_1/RT_1 = (100\ \text{kPa})(0.0010667\ \text{m}^3)/(0.287\ \text{kJ/kg-K})(333\ \text{K})$$
$$= 0.00112\ \text{kg}$$

Mass of fuel injected per cylinder per cycle:

$$m_f = (0.00112)(0.98)(1/19) = 0.0000578\ \text{kg}$$

State 2: Equations (3-52) and (3-53) give temperature and pressure after compression:

$$T_2 = T_1(r_c)^{k-1} = (333\ \text{K})(16)^{0.35} \underline{= 879\ \text{K} = 606°\text{C}}$$
$$P_2 = P_1(r_c)^k = (100\ \text{kPa})(16)^{1.35} \underline{= 4222\ \text{kPa}}$$
$$V_2 = mRT_2/P_2 = (0.00112\ \text{kg})(0.287\ \text{kJ/kg-K})(879\ \text{K})/(4222\ \text{kPa})$$
$$\underline{= 0.000067\ \text{m}^3 = V_c}$$

or using Eq. (2-12):

$$V_2 = V_1/r_c = (0.0010667)/(16) = 0.0000667\ \text{m}^3$$

State x: Heating value of light diesel fuel is obtained from Table A-2 in the Appendix:

$$Q_{in} = m_fQ_{HV} = (0.0000578\ \text{kg})(42{,}500\ \text{kJ/kg}) = 2.46\ \text{kJ}$$

If half of Q_{in} occurs at constant volume, then using Eq. (3-76):

$$Q_{2-x} = 1.23\ \text{kJ} = m_m c_v(T_x - T_2)$$
$$= (0.00112\ \text{kg})(0.821\ \text{kJ/kg-K})(T_x - 879\ \text{K})$$
$$\underline{T_x = 2217\ \text{K} = 1944°\text{C}}$$

$$\underline{V_x = V_2 = 0.0000667 \text{ m}^3}$$

$$P_x = mRT_x/V_x$$
$$= (0.00112 \text{ kg})(0.287 \text{ kJ/kg-K})(2217 \text{ K})/(0.0000667 \text{ m}^3)$$
$$\underline{= 10{,}650 \text{ kPa} = P_{max}}$$

or:

$$P_x = P_2(T_x/T_2) = (4222 \text{ kPa})(2217/879) = 10{,}650 \text{ kPa}$$

State 3:

$$\underline{P_3 = P_x = 10{,}650 \text{ kPa} = P_{max}}$$

Equation (3-81) gives:

$$Q_{x-3} = 1.23 \text{ kJ} = m_m c_p(T_3 - T_x)$$
$$= (0.00112 \text{ kg})(1.108 \text{ kJ/kg-K})(T_3 - 2217 \text{ K})$$
$$\underline{T_3 = 3208 \text{ K} = 2935°\text{C} = T_{max}}$$
$$V_3 = mRT_3/P_3 = (0.00112 \text{ kg})(0.287 \text{ kJ/kg-K})(3208 \text{ K})/(10{,}650 \text{ kPa})$$
$$\underline{= 0.000097 \text{ m}^3}$$

State 4:

$$V_4 = V_1 = 0.0010667 \text{ m}^3$$

Equations (3-64) and (3-65) give temperature and pressure after expansion:

$$T_4 = T_3(V_3/V_4)^{k-1} = (3208 \text{ K})(0.000097/0.0010667)^{0.35}$$
$$\underline{= 1386 \text{ K} = 1113°\text{C}}$$
$$P_4 = P_3(V_3/V_4)^k = (10{,}650 \text{ kPa})(0.000097/0.0010667)^{1.35} \underline{= 418 \text{ kP}}$$

Work out for process x-3 for one cylinder for one cycle using Eq. (3-83):

$$W_{x-3} = P(V_3 - V_x) = (10{,}650 \text{ kPa})(0.000097 - 0.0000667)\text{m}^3 \underline{= 0.323 \text{ k}}$$

Work out for process 3-4 using Eq. (3-66):

$$W_{3-4} = mR(T_4 - T_3)/(1 - k)$$
$$= (0.00112 \text{ kg})(0.287 \text{ kJ/kg-K})(1386 - 3208)\text{K}/(1 - 1.35)$$
$$\underline{= 1.673 \text{ kJ}}$$

Work in for process 1-2 using Eq. (3-56):

$$W_{1-2} = mR(T_2 - T_1)/(1 - k)$$
$$= (0.00112 \text{ kg})(0.287 \text{ kJ/kg-K})(879 - 333)\text{K}/(1 - 1.35)$$
$$= -0.501 \text{ kJ}$$
$$W_{net} = (+0.323) + (+1.673) + (-0.501) = +1.495 \text{ kJ}$$

2) Equation (3-88) gives indicated thermal efficiency:

$$(\eta_t)_{DUAL} = |W_{net}|/|Q_{in}| = (1.495 \text{ kJ})/(2.46 \text{ kJ}) = \underline{0.607 = 60.7\%}$$

Pressure ratio:

$$\alpha = P_x/P_2 = 10{,}650/4222 = 2.52$$

Cutoff ratio:

$$\beta = V_3/V_x = 0.000097/0.0000667 = 1.45$$

Using Eq. (3-89) to find thermal efficiency:

$$\begin{aligned}(\eta_t)_{DUAL} &= 1 - (1/r_c)^{k-1}[\{\alpha\beta^k - 1\}/\{k\alpha(\beta - 1) + \alpha - 1\}] \\ &= 1 - (1/16)^{0.35}[\{(2.52)(1.45)^{1.35} - 1\}/\{(1.35)(2.52)(1.45 - 1) + 2.52 - 1\}] \\ &= 0.607\end{aligned}$$

5) Mass of air entering one cylinder during intake:

$$m_a = (0.00112 \text{ kg})(0.98) = 0.00110 \text{ kg}$$

Volumetric efficiency is found using Eq. (2-69):

$$\begin{aligned}\eta_v &= m_a/\rho_a V_d = (0.00110 \text{ kg})/(1.181 \text{ kg/m}^3)(0.001 \text{ m}^3) \\ &= \underline{0.931 = 93.1\%}\end{aligned}$$