INTERNAL COMBUSTION ENGINES

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Lecture # 5 (Engine Cycles - Problems)

DUAL CYCLE

1. If Eqs. (31) and (73) 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.

2. 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.

$$(\eta_t)_{\text{OTTO}} = 1 - (1/r_c)^{k-1} \tag{31}$$

$$(\eta_t)_{\text{DIESEL}} = 1 - (1/r_c)^{k-1}[(\beta^k - 1)/\{k(\beta - 1)\}] \tag{73}$$

DUAL CYCLE

1. The modern high-speed CI engine accomplishes this in part by a simple operating change from early diesel engines.
2. 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.
3. 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.
4. The last of the fuel is still being injected at TDC, and combustion of this fuel keeps the pressure high into the expansion stroke.
5. The air-standard cycle used to analyze this modern CI engine cycle is called a Dual cycle or sometimes a Limited Pressure cycle.
6. 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.

DUAL CYCLE

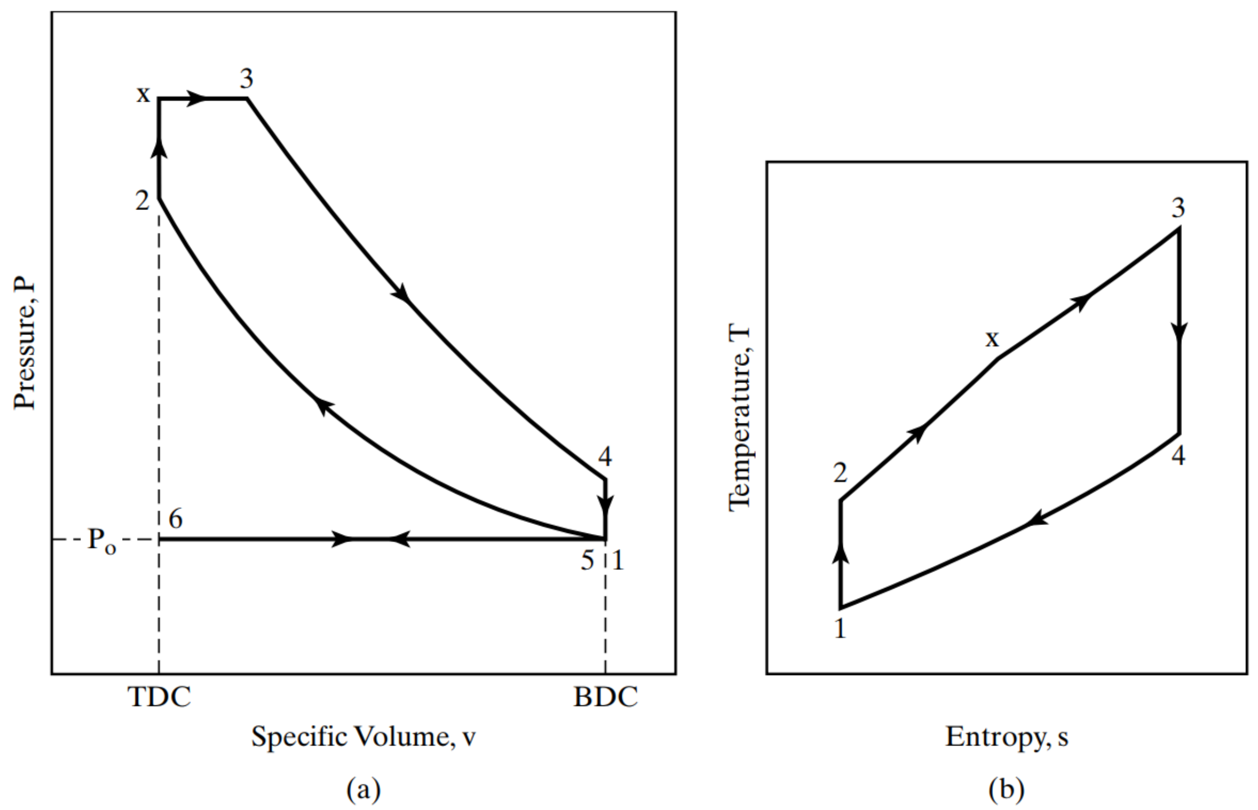


FIGURE 11

Air-standard Dual cycle, 6-1-2-x-3-4-5-6, which approximates the four-stroke cycle of a modern CI engine on **(a)** pressure-specific volume coordinates, and **(b)** temperature-entropy coordinates.

DUAL 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.

Process 2-*x*—constant-volume heat input (first part of combustion).

All valves closed:

$$V_x = V_2 = V_{\mathrm{TDC}} \tag{74}$$

$$w_{2-x} = 0 \tag{75}$$

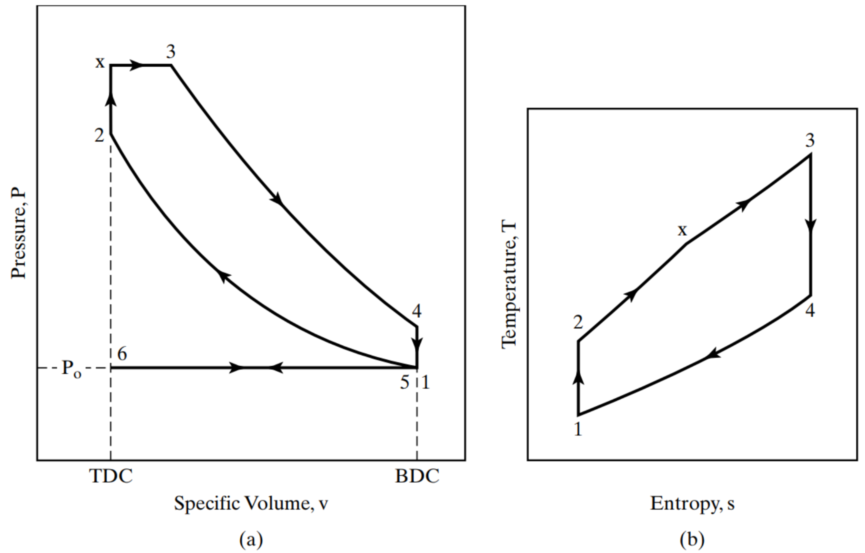
$$Q_{2-x} = m_m c_v(T_x - T_2) = (m_a + m_f)c_v(T_x - T_2) \tag{76}$$

$$q_{2-x} = c_v(T_x - T_2) = (u_x - u_2) \tag{77}$$

$$P_x = P_{\max} = P_2(T_x/T_2) \tag{78}$$

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

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



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DUAL CYCLE

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

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

Cutoff ratio:

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

Heat in:

$$Q_{in} = Q_{2-x} + Q_{x-3} = m_f Q_{HV} \eta_c \tag{86}$$

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

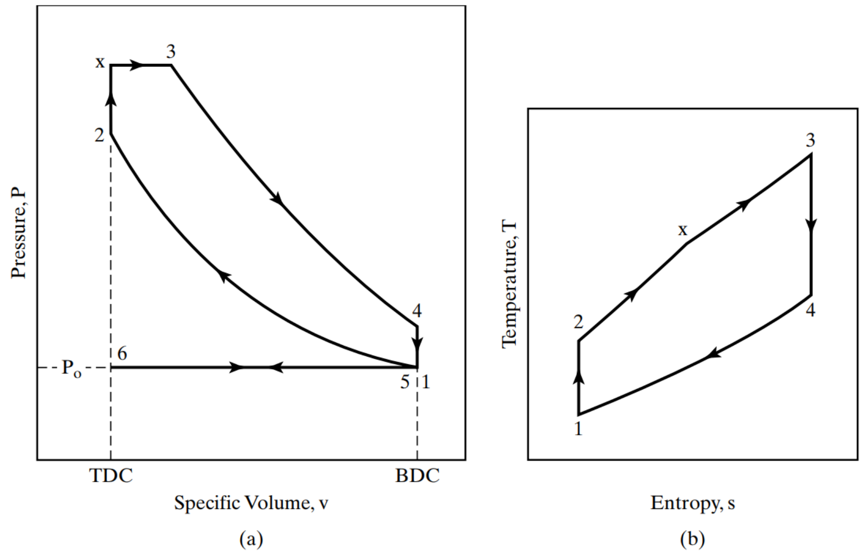


FIGURE 11

Air-standard Dual cycle, 6-1-2-x-3-4-5-6, which approximates the four-stroke cycle of a modern CI engine on **(a)** pressure-specific volume coordinates, and **(b)** temperature-entropy coordinates.

DUAL CYCLE

Thermal efficiency of Dual cycle:

$$
\begin{aligned}
(\eta_t)_{\mathrm{DUAL}} &= |w_{\mathrm{net}}|/|q_{\mathrm{in}}| = 1 - (|q_{\mathrm{out}}|/|q_{\mathrm{in}}|) \\
&= 1 - c_v(T_4 - T_1)/[c_v(T_x - T_2) + c_p(T_3 - T_x)] \\
&= 1 - (T_4 - T_1)/[(T_x - T_2) + k(T_3 - T_x)] \qquad (88)
\end{aligned}
$$

This can be rearranged to give

$$(\eta_t)_{\mathrm{DUAL}} = 1 - (1/r_c)^{k-1}[\{\alpha\beta^k - 1\}/\{k\alpha(\beta - 1) + \alpha - 1\}] \qquad (89)$$

where

r_c = compression ratio
$k = c_p/c_v$
α = pressure ratio
β = cutoff ratio

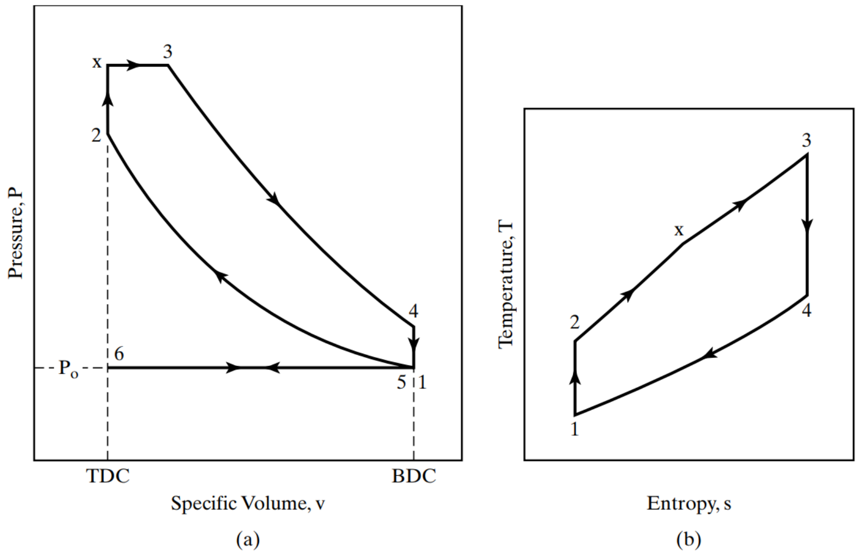


FIGURE 11

Air-standard Dual cycle, 6-1-2-x-3-4-5-6, which approximates the four-stroke cycle of a modern CI engine on **(a)** pressure-specific volume coordinates, and **(b)** temperature-entropy coordinates.

$$(\eta_t)_{\mathrm{actual}} \approx 0.85(\eta_t)_{\mathrm{DIESEL}} \qquad (90)$$

$$(\eta_t)_{\mathrm{actual}} \approx 0.85(\eta_t)_{\mathrm{DUAL}} \qquad (91)$$

COMPARISON OF OTTO, DIESEL, AND DUAL CYCLES

1. Under same compression ratio:

$$(\eta_t)_{\mathrm{OTTO}} > (\eta_t)_{\mathrm{DUAL}} > (\eta_t)_{\mathrm{DIESEL}}$$

However, this is not the best way to compare these three cycles, because they do not operate on the same compression ratio.

Compression ignition engines that operate on the Dual cycle or Diesel cycle have much higher compression ratios than do spark ignition engines operating on the Otto cycle.

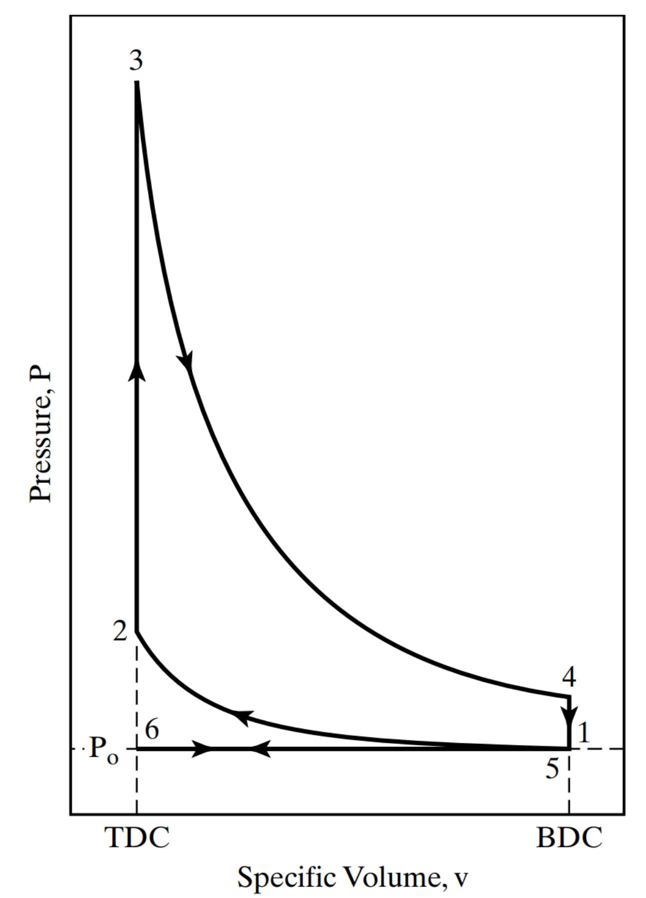
$$(\eta_t)_{\mathrm{DIESEL}} > (\eta_t)_{\mathrm{DUAL}} > (\eta_t)_{\mathrm{OTTO}} \qquad (94)$$

Comparing the ideas of Eqs. (93) and (94) would suggest that the most efficient engine would have combustion as close as possible to constant volume but would be compression ignition and operate at the higher compression ratios which that requires. This is an area where more research and development is needed.

EXAMPLE 1: OTTO CYCLE

A four-cylinder, 2.5-liter, SI automobile engine operates at WOT on a four-stroke air-standard Otto cycle at 3000 RPM. The engine has a compression ratio of 8.6:1, a mechanical efficiency of 86%, and a stroke-to-bore ratio $S/B = 1.025$. Fuel is isooctane with AF $= 15$, a heating value of 44,300 kJ/kg, and combustion efficiency $\eta_c = 100\%$. At the start of the compression stroke, conditions in the cylinder combustion chamber are 100 kPa and 60°C. It can be assumed that there is a 4% exhaust residual left over from the previous cycle.

Do a complete thermodynamic analysis of this engine.

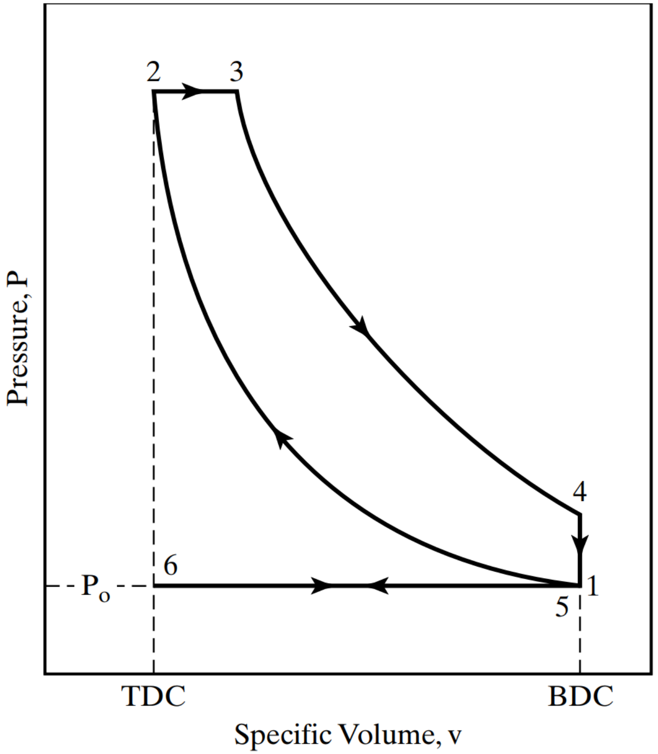


EXAMPLE 2: DIESEL CYCLE

Example Problem 4

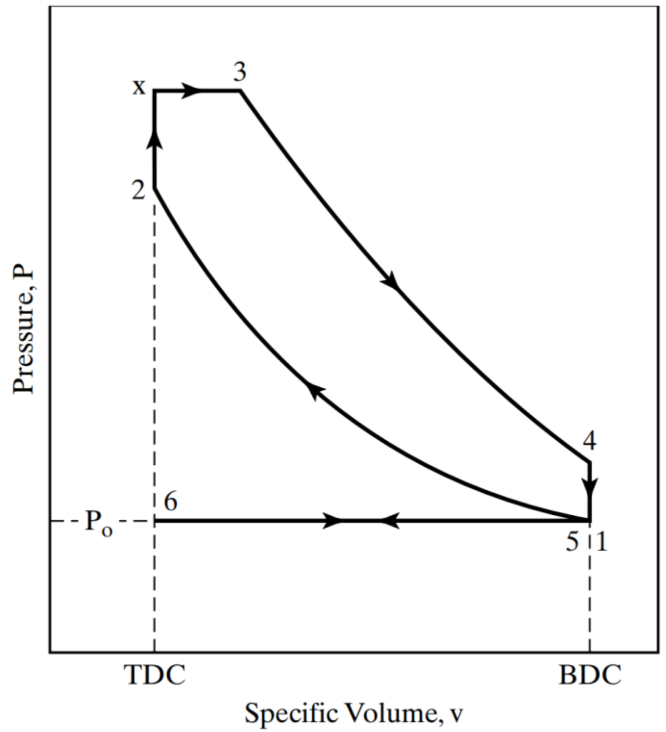
A large vintage straight six CI truck engine operates on an air-standard Diesel cycle (Fig. 8) using heavy diesel fuel with a combustion efficiency of 98%. The engine has a compression ratio of 16.5:1. Temperature and pressure in the cylinders at the start of the compression stroke are 55°C and 102 kPa, and maximum cycle temperature is 2410°C. Calculate:

1. temperature, pressure, and specific volume at each state of the cycle
2. air–fuel ratio of the cylinder gas mixture
3. cylinder temperature when the exhaust valve opens
4. indicated thermal efficiency of the engine



EXAMPLE 3: DUAL CYCLE

A small truck has a four-cylinder, four-liter CI engine that operates on the air-standard Dual cycle (Fig. 11) 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.



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

END OF THE LECTURE