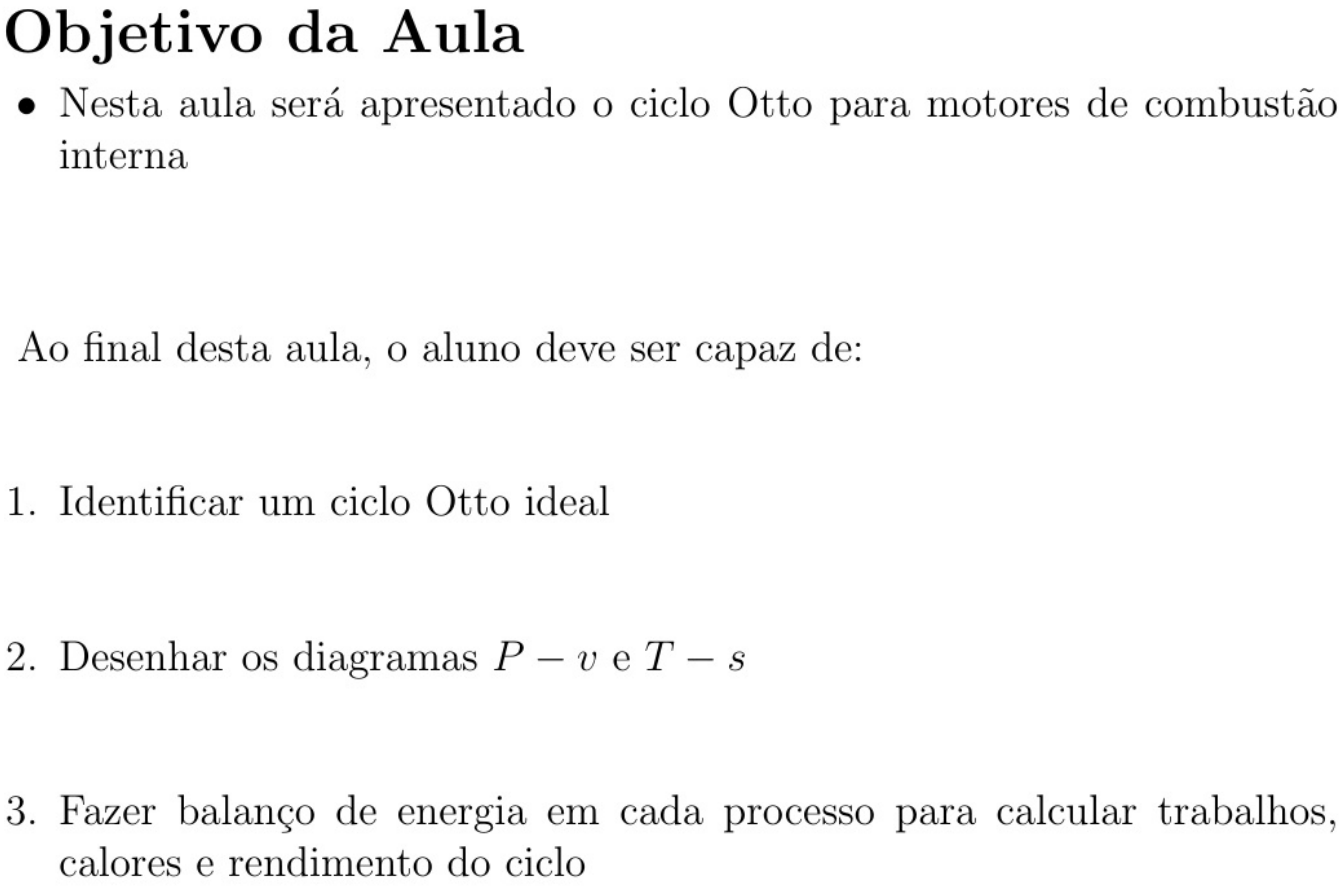
Ciclo de potência a gás
Otto



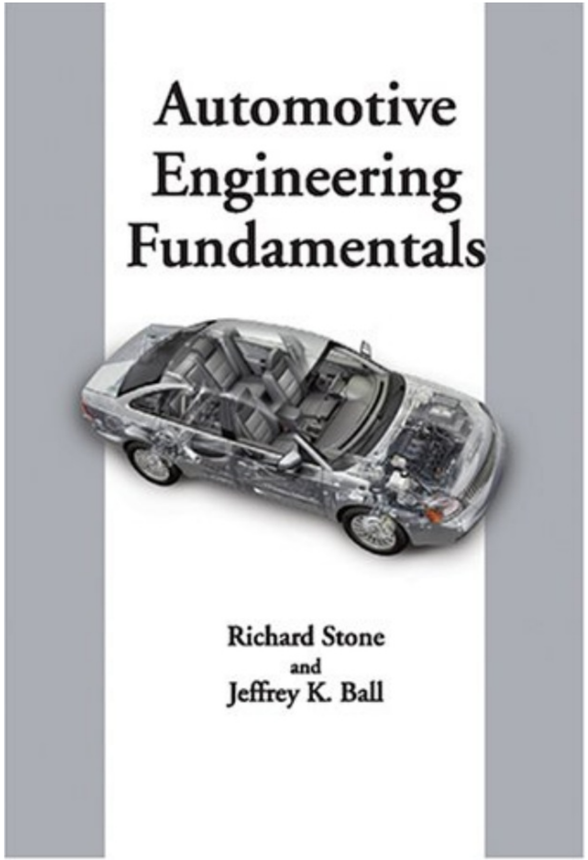
Objetivo da Aula

- Nesta aula será apresentado o ciclo Otto para motores de combustão interna

Ao final desta aula, o aluno deve ser capaz de:

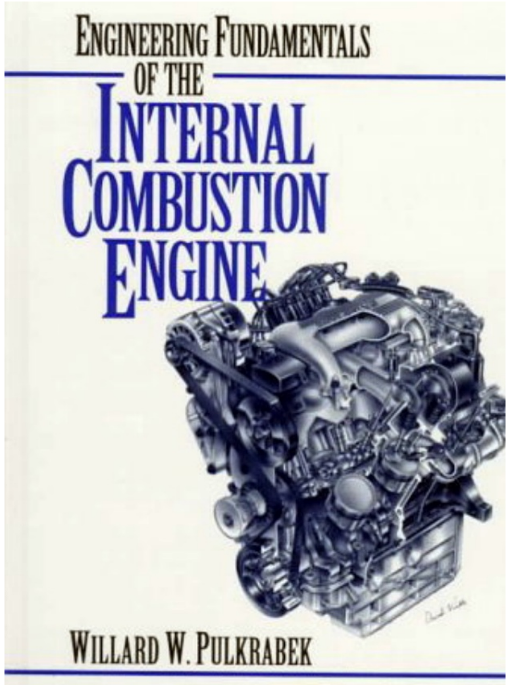
1. Identificar um ciclo Otto ideal
2. Desenhar os diagramas $P-v$ e $T-s$
3. Fazer balanço de energia em cada processo para calcular trabalhos, calores e rendimento do ciclo

Referências bibliográficas



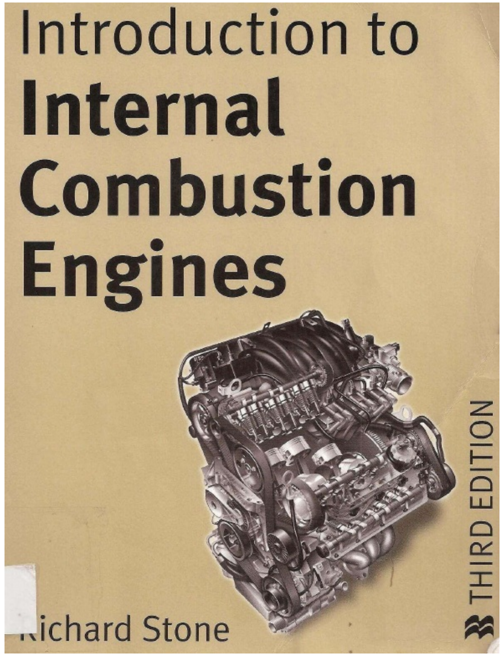
Automotive Engineering Fundamentals

Richard Stone
and
Jeffrey K. Ball



ENGINEERING FUNDAMENTALS OF THE INTERNAL COMBUSTION ENGINE

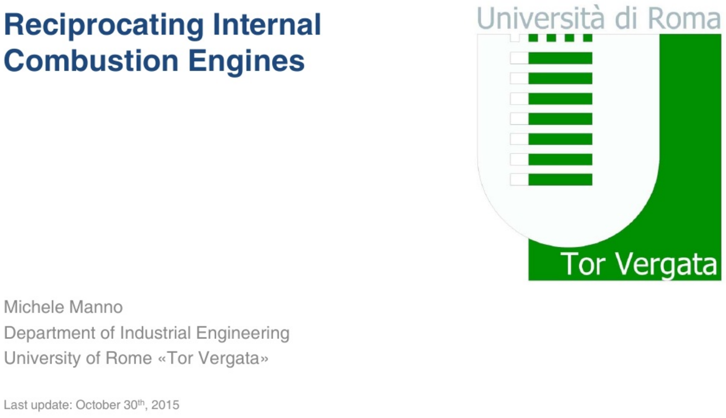
WILLARD W. PULKRABEK



Introduction to Internal Combustion Engines

THIRD EDITION

Richard Stone



Reciprocating Internal Combustion Engines

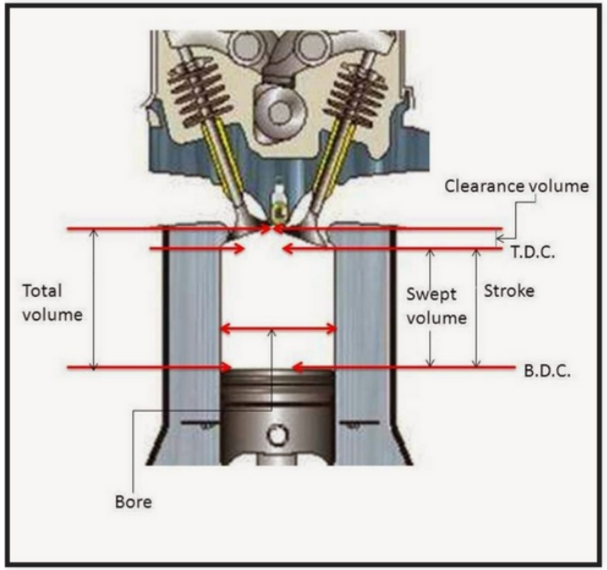
Università di Roma
Tor Vergata

Michele Manno
Department of Industrial Engineering
University of Rome «Tor Vergata»

Last update: October 30th, 2015

Parâmetros físicos importantes

MOVIMENTO DO PISTÃO

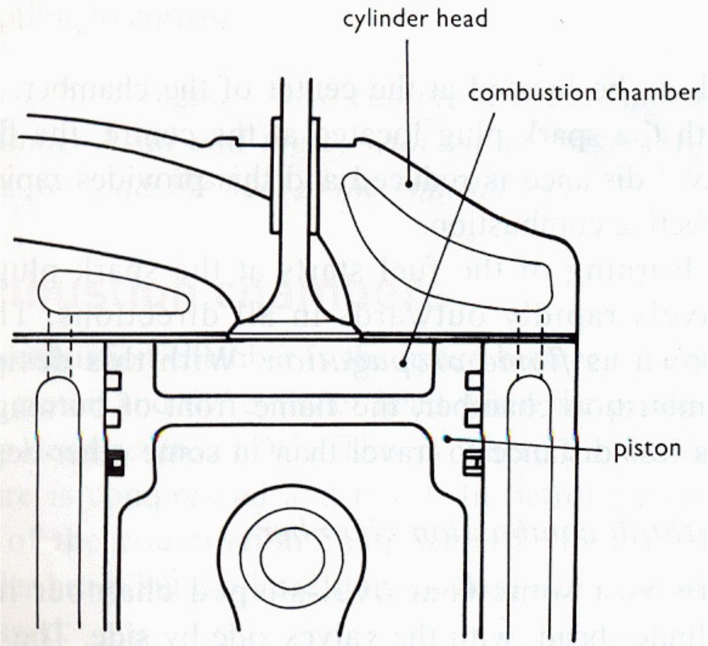


Taxa de compressão: razão entre volumes máximo e mínimo.

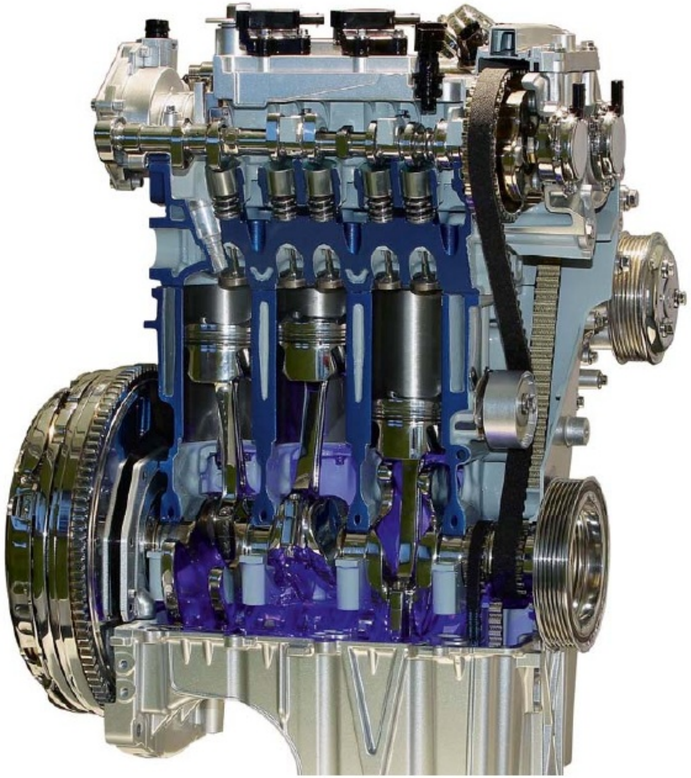
$$rc = \frac{V_t}{V_c}$$

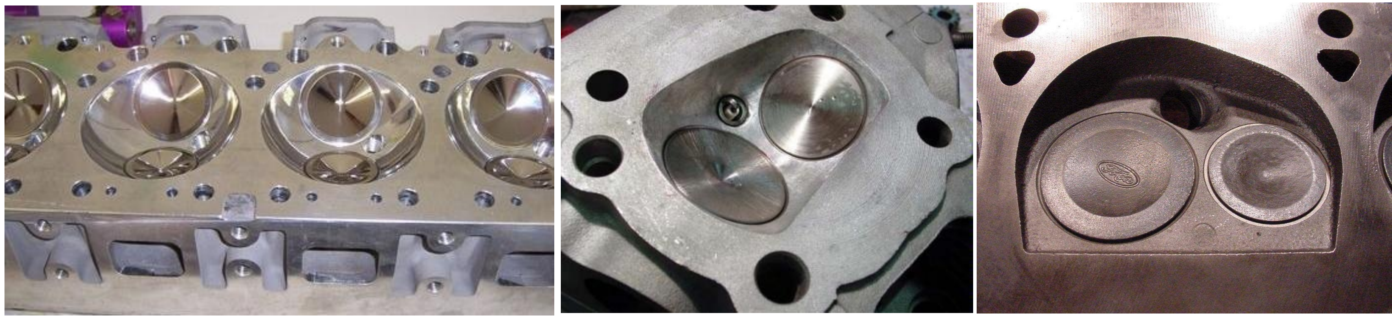
SI: $8 \leq rc \leq 12$

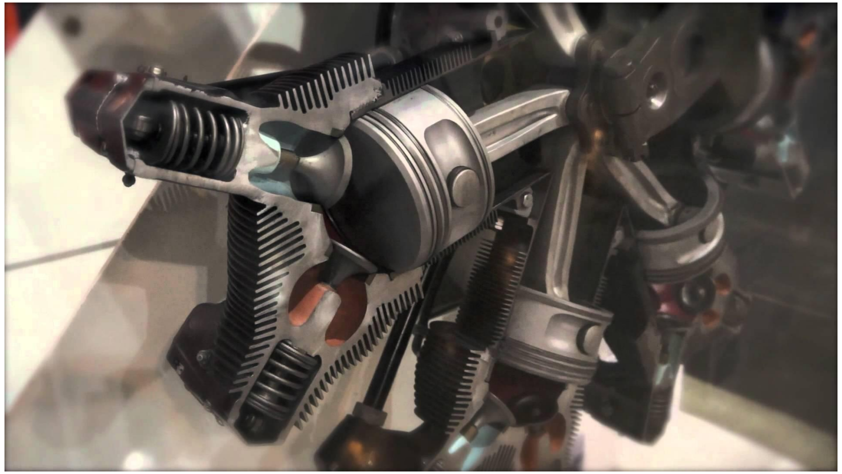
CI: $12 \leq rc \leq 24$



Câmara de Combustão e Volume residual







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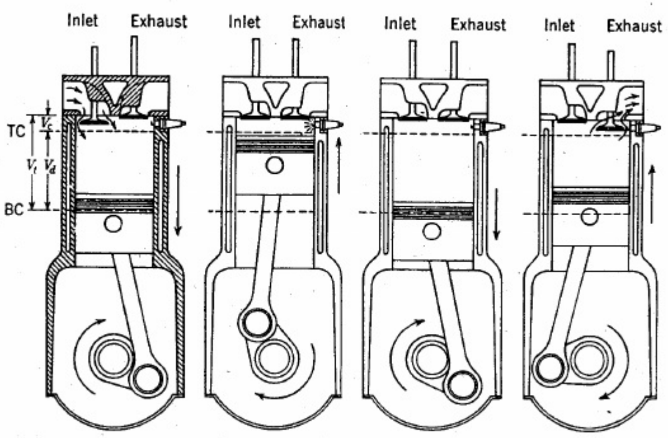
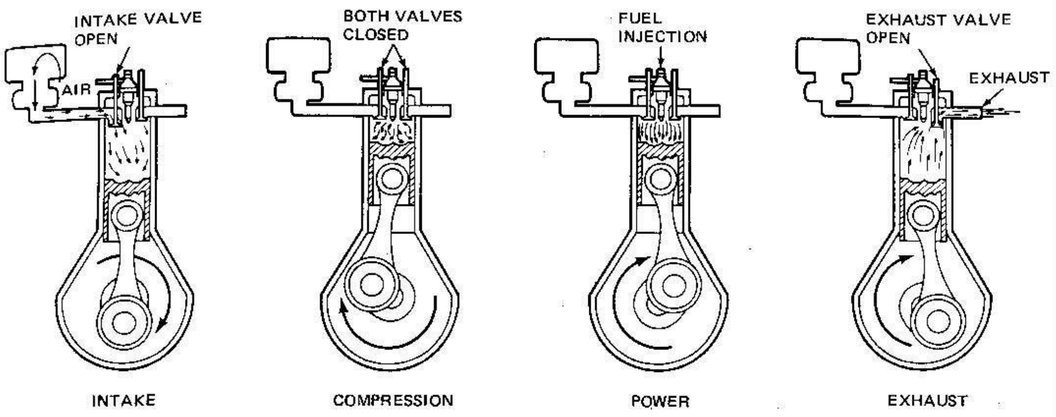
O ciclo Otto de 4 tempos

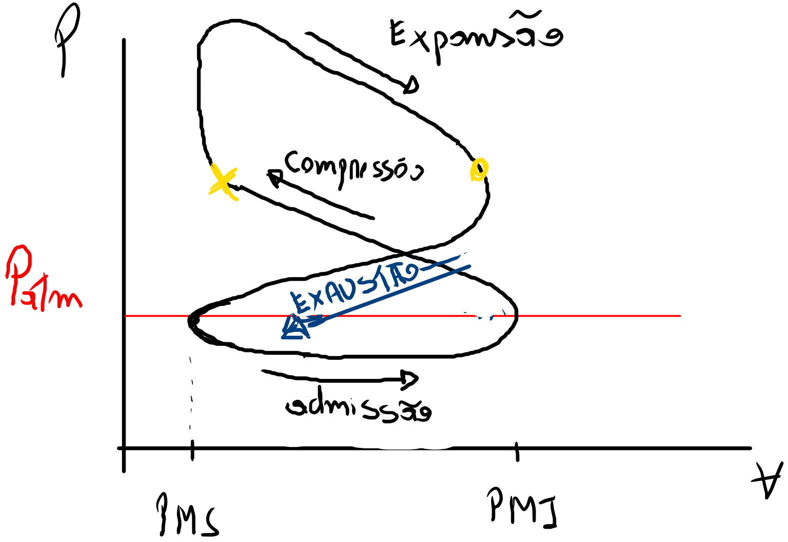


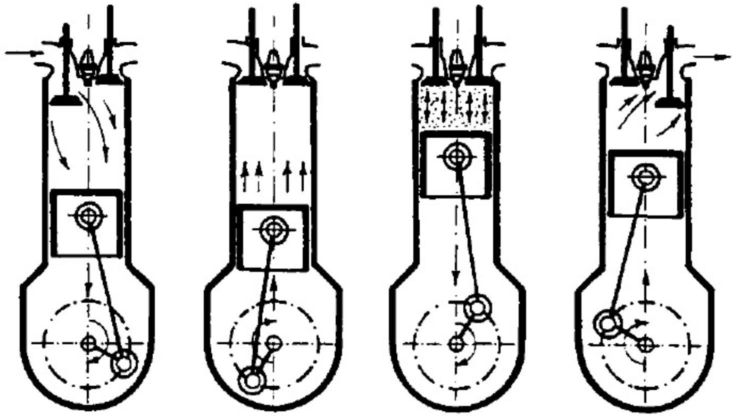
(a) Intake (b) Compression (c) Expansion (d) Exhaust

FIGURE 1-2
The four-stroke operating cycle.[10]

Heywook, 1988







Manno, 2015

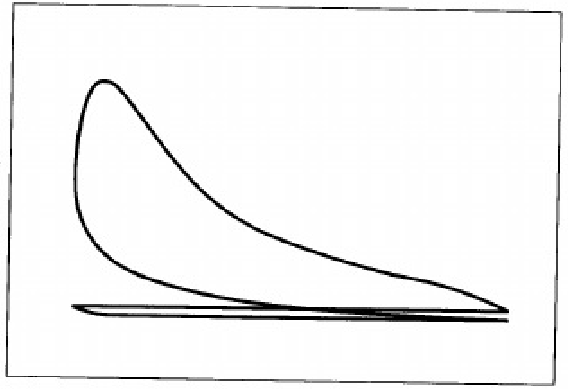


Figure 2-6 Indicator diagram for a typical four stroke cycle SI engine. An indicator diagram plots cylinder pressure as a function of combustion chamber volume over a 720° cycle. The diagram is generated on an oscilloscope using a pressure transducer mounted in the combustion chamber and a position sensor mounted on the piston or crankshaft.

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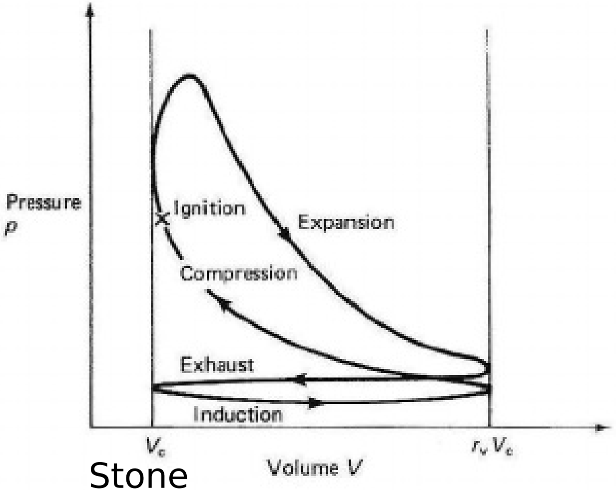
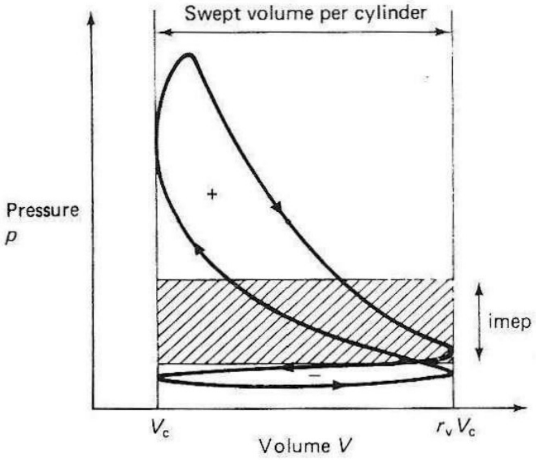


Stone



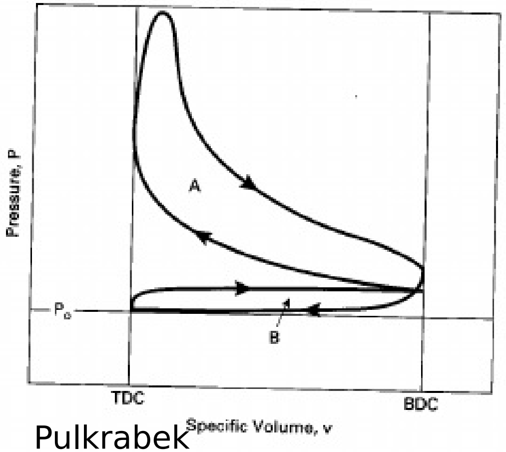


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Figure 2-10 Four-stroke cycle of a SI engine equipped with a supercharger or turbocharger, plotted on P-v coordinates. For this cycle intake pressure is greater than exhaust pressure and the pump work loop represents positive work.

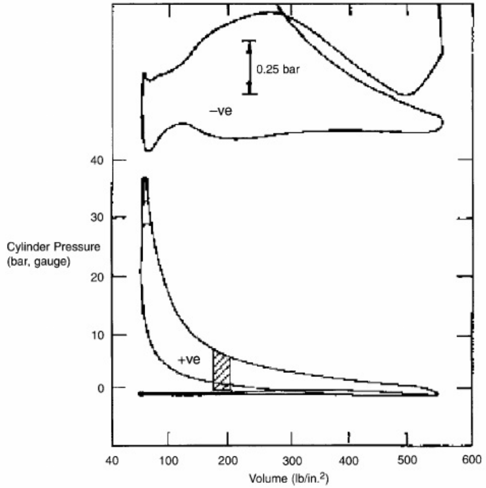
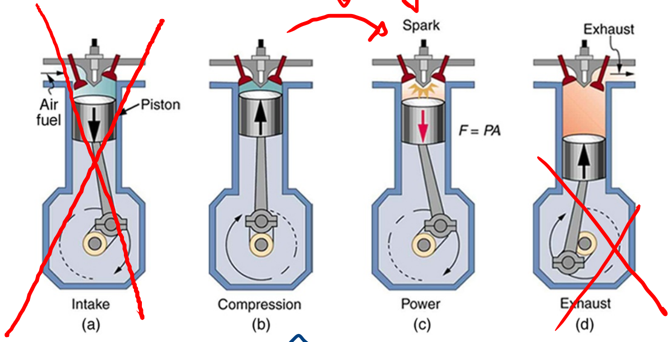


Figure 2.3. *The pressure–volume or indicator from a Rover M16 engine operating at 2000 rpm, with an enlargement of the pumping loop; bmep = 3.8 bar, and imep = 4.6 bar (including the pumping work of 0.45 bar pmep). Adapted from Stone (1999).*

Ball & Stone, 2004

Considerações



Q_q

Q_F

De maneira semelhante ao ciclo Brayton, a análise a ar padrão considera:

1. quantidade fixa de ar no interior do pistão-cilindro Sistema FECHADO!
2. sempre ar (não é convertido em produtos de combustão)
3. sempre gás ideal
4. Processo de combustão substituído por transferência de calor de uma fonte externa à *volume* constante
5. Não há processos de admissão nem exaustão.
6. Processos internamente reversíveis Eq. isent.
7. A análise a ar frio considera calores específicos constantes avaliados à temperatura ambiente (298K)

r_c

$$\boxed{\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}}$$

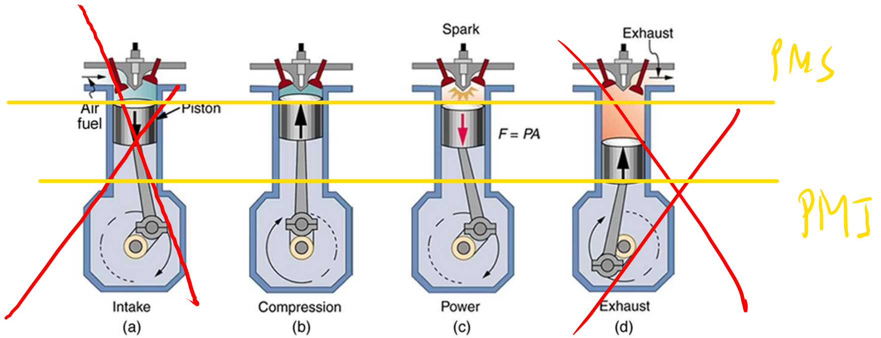
c_p

c_v

$\Rightarrow$ $h = c_p . T$

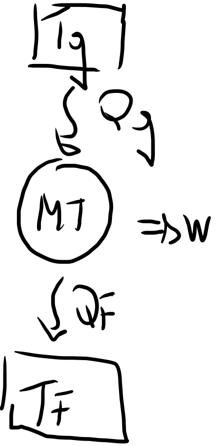
$u = c_v . T$

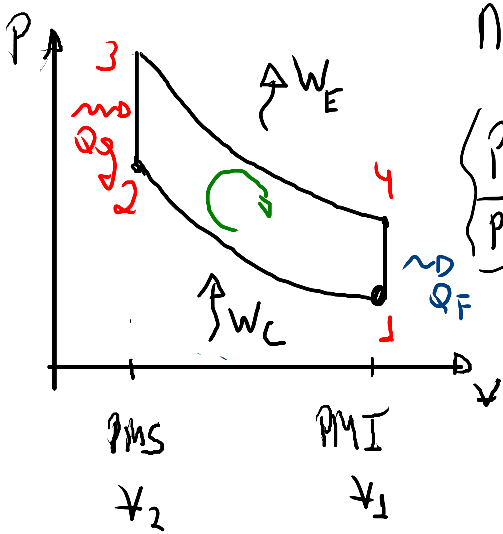
Processos e 1ª Lei no ciclo otto



Processos:

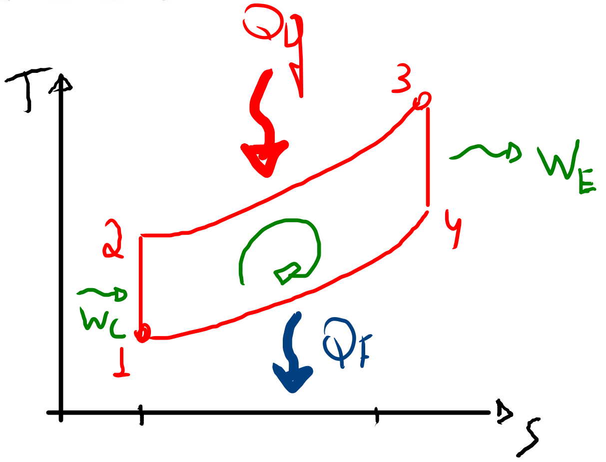
1. 1-2: Compressão adiabática E REVERSÍVEL (Isoentrópica)
2. 2-3: Transferência calor a volume constante (Adição)
3. 3-4: Expansão adiabática E REVERSÍVEL (ISOENTRÓPICA)
4. 4-1: Transferência calor a volume constante (Rejeição)

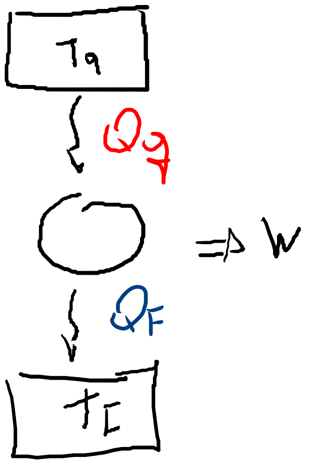




$$\eta = \frac{V_1}{V_2}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$





$1 \rightarrow 2)$

$$\phi \quad s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$\phi \quad s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{\forall_2}{\forall_1}\right) \checkmark$$

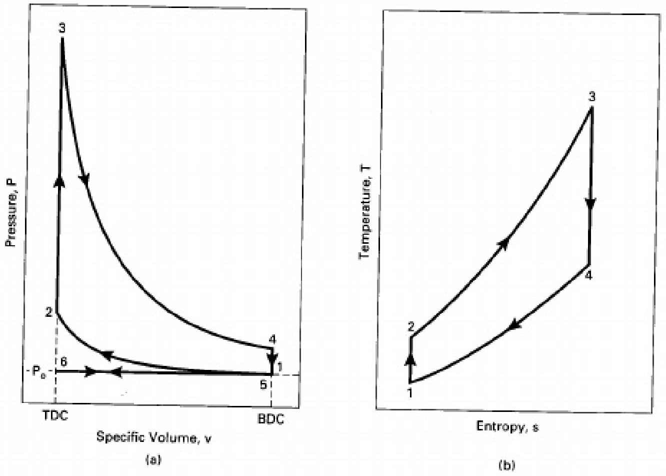


Figure 3-2 Otto cycle, 6-1-2-3-4-5-6, on (a) pressure-specific volume coordinates, and (b) temperature-entropy coordinates.

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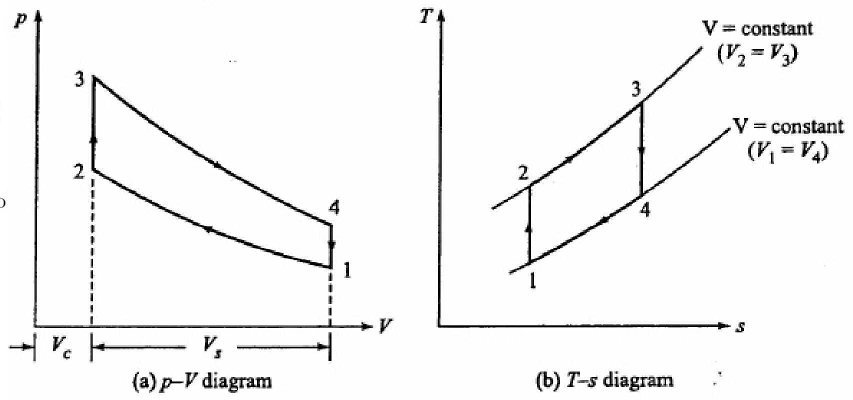
ocessos:

1. 1-2: Compressão adiabática
2. 2-3: Transferência calor a volume constante (Adição)
3. 3-4: Expansão adiabática
4. 4-1: Transferência calor a volume constante (Rejeição



(a) p–V diagram (b) T–s diagram

Figure 2.1 Otto cycle.

Gupta, 2009

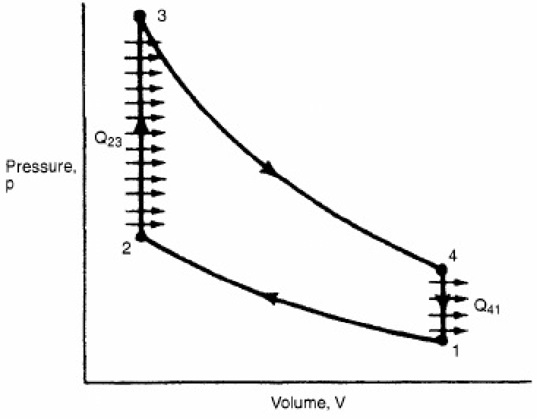
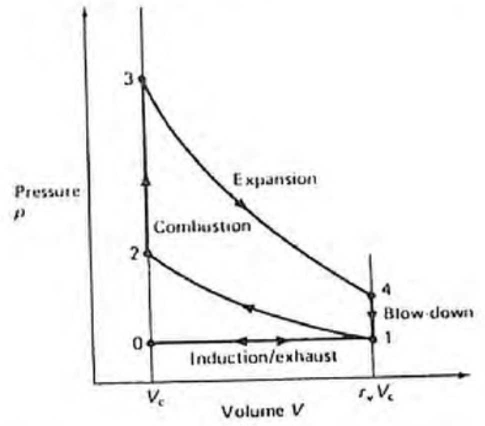
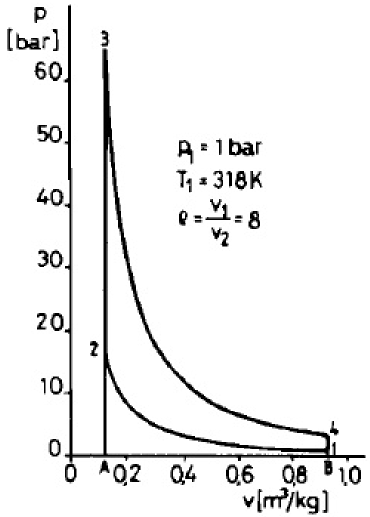


Figure 2.4. *The air standard Otto cycle (Stone, 1999).*



Stone

Constant-volume
«Otto»



Manno, 2005

2015

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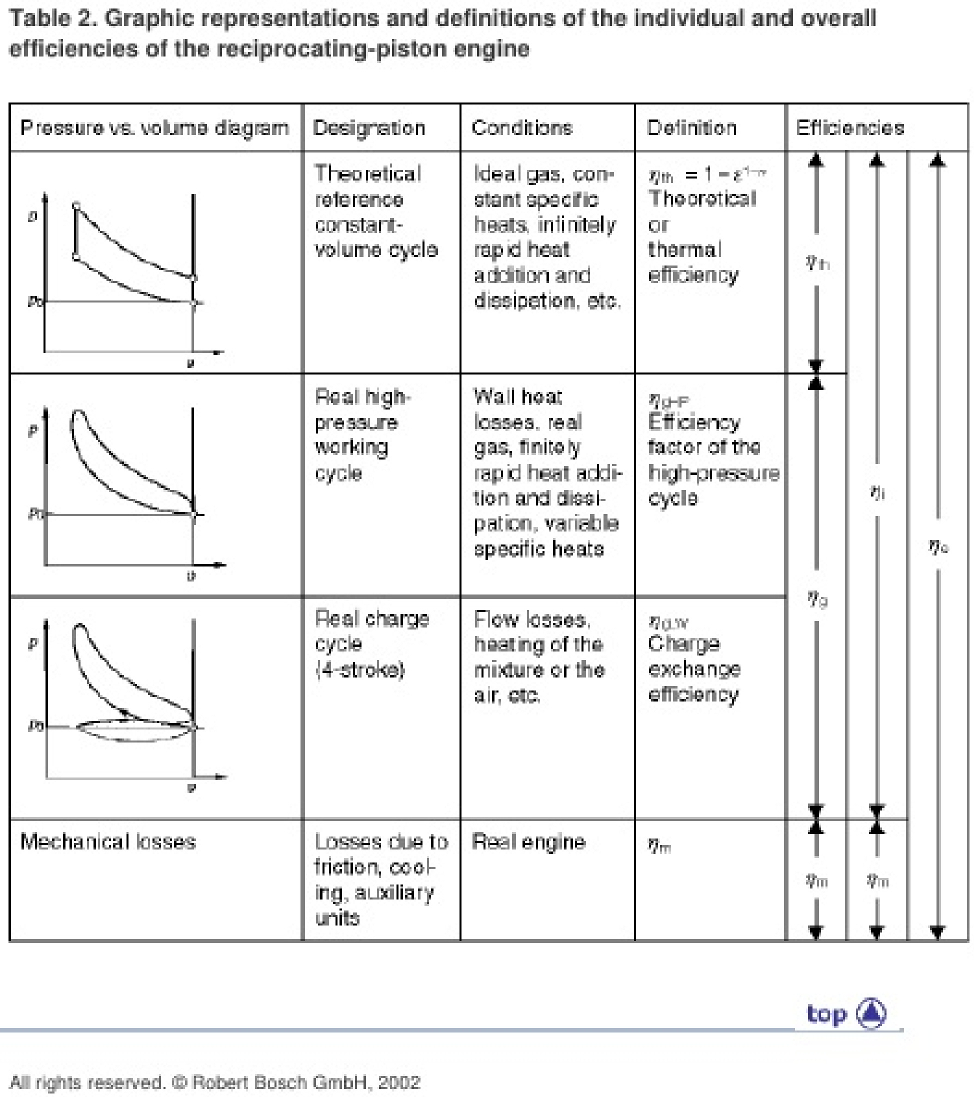

Table 2. Graphic representations and definitions of the individual and overall efficiencies of the reciprocating-piston engine

Pressure vs. volume diagram	Designation	Conditions	Definition	Efficiencies		
	Theoretical reference constant-volume cycle	Ideal gas, constant specific heats, infinitely rapid heat addition and dissipation, etc.	$\eta_{th} = 1 - \varepsilon^{1-\kappa}$ Theoretical or thermal efficiency	η_{th}	η_i	η_e
	Real high-pressure working cycle	Wall heat losses, real gas, finitely rapid heat addition and dissipation, variable specific heats	η_{g-F} Efficiency factor of the high-pressure cycle	η_g		
	Real charge cycle (4-stroke)	Flow losses, heating of the mixture or the air, etc.	$\eta_{g,w}$ Charge exchange efficiency			
Mechanical losses	Losses due to friction, cooling, auxiliary units	Real engine	η_m	η_m	η_m	

top

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Processos e 1ª Lei no ciclo otto

Processos:

1. 1-2: Compressão adiabática
2. 2-3: Transferência calor a volume constante (Adição)
3. 3-4: Expansão adiabática
4. 4-1: Transferência calor a volume constante (Rejeição)

$$dE = \delta Q + \delta W$$

$$dE = dU + \cancel{dE_K} + \cancel{dE_P}$$

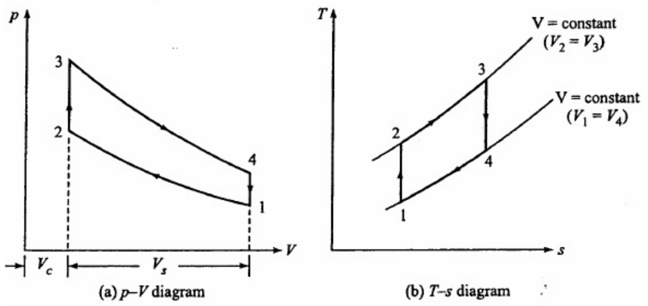


Figure 2.1 Otto cycle.

Gupta, 2009

1ª Lei:

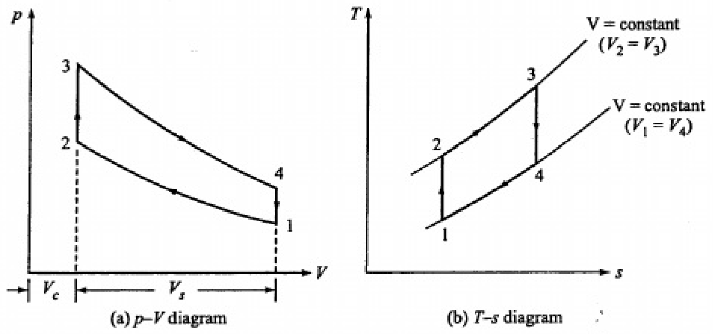
1. 1-2: $Q_{12} = 0$; $W_{12} = dU_{12} = \underline{c_v(T_2 - T_1)}$
2. 2-3: $W_{23} = 0$; $Q_{23} = dU_{23} = U_3 - U_2 \Rightarrow Q_{23} = \underline{c_v(T_3 - T_2)}$
3. 3-4: $Q_{34} = 0$; $W_{34} = dU_{34} = U_4 - U_3 \Rightarrow W_{34} = \underline{c_v(T_4 - T_3)}$
4. 4-1: $W_{41} = 0$; $Q_{41} = dU_{41} = U_1 - U_4 \Rightarrow Q_{41} = \underline{c_v(T_1 - T_4)}$

Cálculo dos estados termodinâmicos

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k}$$

Processos:

1. 1-2: Compressão adiabática
2. 2-3: Transferência calor a volume constante (Adição)
3. 3-4: Expansão adiabática
4. 4-1: Transferência calor a volume constante (Rejeição)



(a) p–V diagram (b) T–s diagram

Figure 2.1 Otto cycle.

Gupta, 2009

$$\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{v_2}{v_1}\right)^{1-k} \rightarrow \frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^{(1-k)\frac{k}{k-1}} \rightarrow \frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^{-k}$$

Estado	P[KPa]	T[°C]	v[$m|3/Kg$]	R[KJ/Kg.K]
1	P_1	T_1	v_1	R
2	P_2	T_2	v_2	R
3	P_3	T_3	v_3	R
4	P_4	T_4	v_4	R

$$P_3 v_3 = RT_3 \rightarrow P_3 = \frac{RT_3}{v_3}$$

$$\frac{Pv}{T} = R \Rightarrow \frac{P_3 \cancel{v_3}}{T_3} = \frac{P_2 \cancel{v_2}}{T_2}$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}} = \left(\frac{v_4}{v_3}\right)^{1-k}$$

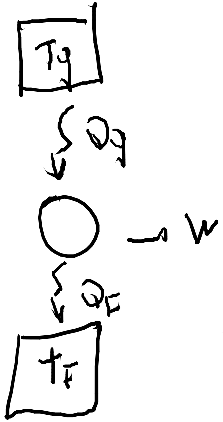
$$Pv = R.T \quad \{ P\forall = mRT$$

$$R = 287 \frac{J}{KgK}$$

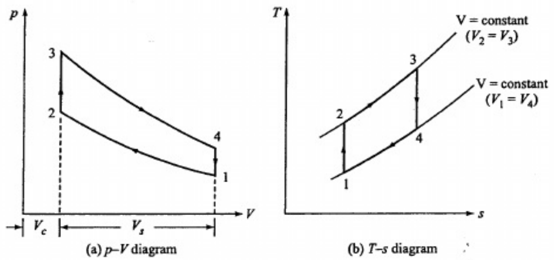
Rendimento

$$\eta_{Otto} = 1 - \frac{T_4 - T_1}{r_v^{\gamma-1}(T_4 - T_1)} = 1 - \frac{1}{r_v^{\gamma-1}}$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{Q_q - Q_F}{Q_q} \Rightarrow \eta = 1 - \frac{Q_F}{Q_q}$$



$Q_q \rightarrow$



(a) p–V diagram (b) T–s diagram

Figure 2.1 Otto cycle.

Gupta, 2009

$$\eta = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)}$$

$$\eta = 1 - \frac{T_1\cancel{\left(\frac{T_4}{T_1} - 1\right)}}{T_2\cancel{\left(\frac{T_3}{T_2} - 1\right)}}$$

$$\boxed{\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{n^{k-1}}}$$

$$\left\{ \begin{aligned} &\frac{T_2}{T_1} = \left(\frac{v_2}{v_1}\right)^{1-k} = \left(\frac{v_1}{v_2}\right)^{k-1} = n^{k-1} \\ &\frac{T_4}{T_3} = \left(\frac{v_4}{v_3}\right)^{1-k} \Rightarrow \frac{T_4}{T_3} = n^{1-k} \Rightarrow \frac{T_3}{T_4} = n^{k-1} \\ &\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2} \end{aligned} \right.$$

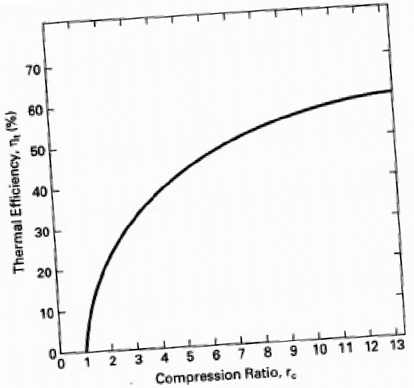


Figure 3-3 Indicated thermal efficiency as a function of compression ratio for SI engines operating at WOT on air-standard Otto cycle ($k = 1.35$).

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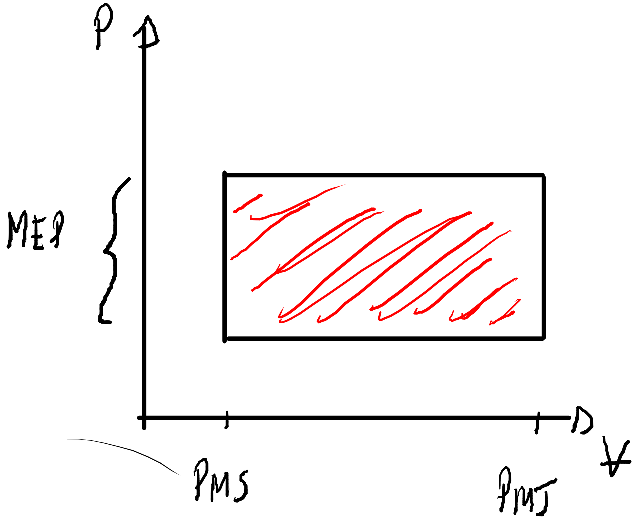
Pressão efetiva média



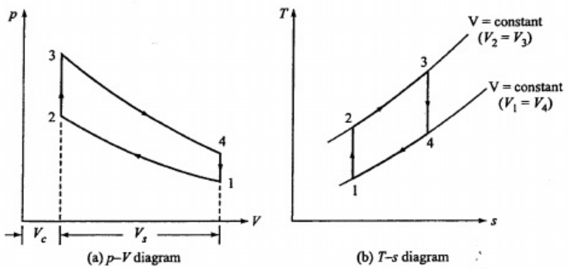
$$MEP = \frac{W_{lig}}{\forall_{disL}} \Rightarrow W_{lig} = MEP \cdot \forall_{disL}$$

$$\frac{J}{m^3} = \frac{N \cdot m}{m^3} = \frac{N}{m^2} = Pa$$

$$\frac{\frac{J}{\cancel{kg}}}{\frac{m^3}{\cancel{kg}}} = \frac{J}{m^3} = Pa$$

Procedimento de Solução

1) Diagrama P-v e T-s



(a) p–V diagram (b) T–s diagram

Figure 2.1 Otto cycle.

Gupta, 2009

2) Tabela de Estados

Gupta, 2009

Estado	P[KPa]	T[°C]	v[$m\|3/Kg$]	R[KJ/Kg.K]
1	P_1	T_1	v_1	R
2	P_2	T_2	v_2	R
3	P_3	T_3	v_3	R
4	P_4	T_4	v_4	R

3) Tabela de Processos

Processos:

1. 1-2: Compressão adiabática
2. 2-3: Transferência calor a volume constante (Adição)
3. 3-4: Expansão adiabática
4. 4-1: Transferência calor a volume constante (Rejeição)

Processo	q[KJ/Kg]	w[KJ/Kg]
1-2	0	$c_v(T_2 - T_1)$
2-3	$c_v(T_3 - T_2)$	0
3-4	0	$c_v(T_4 - T_3)$
4-1	$c_v(T_1 - T_4)$	0
$\sum$	q_{liq}	w_{liq}

$$P\vartheta = R.T$$

$$R = \frac{P\vartheta}{T} \qquad R = 287 \frac{J}{kg\,K}$$

$$de = \delta q + \delta w$$

$$\eta = \frac{W_{liq}}{Q_g}$$

$$MEP = \frac{W_{liq}}{V_{desl.}}$$

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