INTRODUÇÂO

1.Conceito Fundamental

Motores térmico são máquinas que transformam energia térmica em energia mecânica.

2.Classificação dos motores quanto à combustão:

Motores à combustão interna

Motores à combustão externa

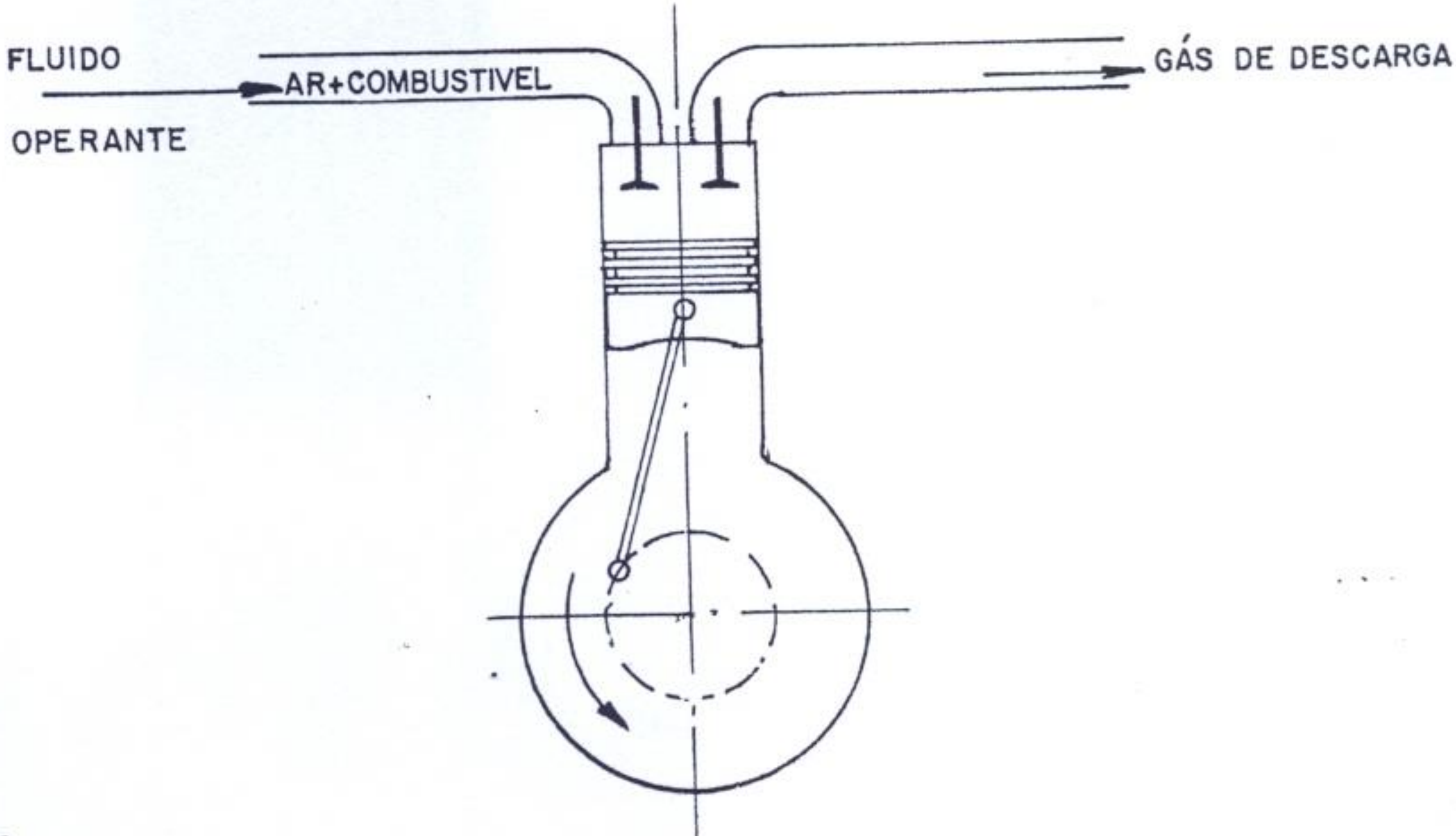


Fig. 1

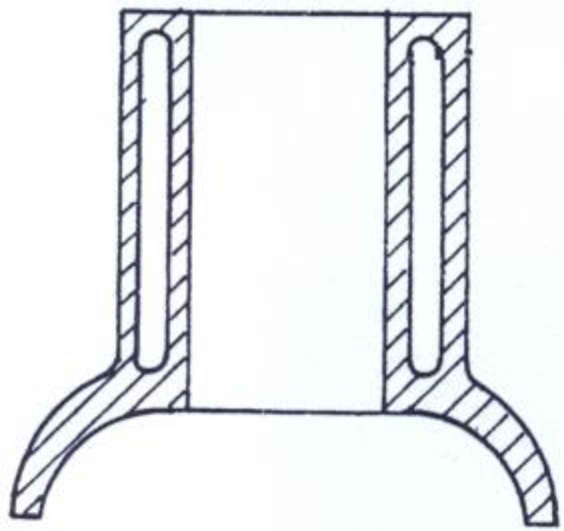
3.PRINCIPAIS COMPONENTES

3.1Componentes (órgãos) fixos:

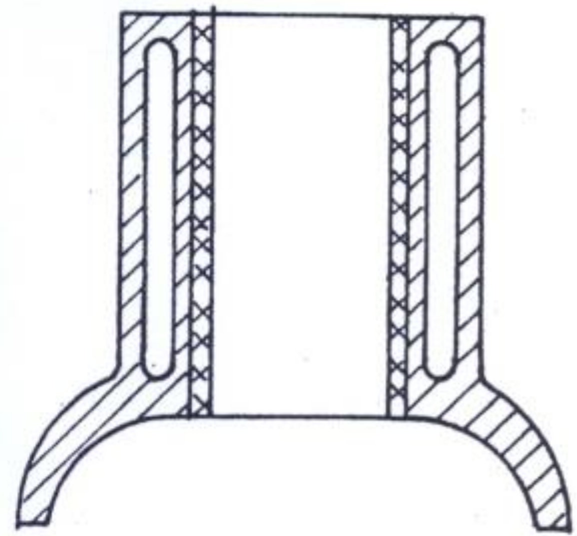
- Cilindro
- Bloco
- Cárter
- Cabeçote
- Câmara de combustão
- Sede de válvula
- Guia de Válvula

3.2 Componentes (órgãos) móveis:

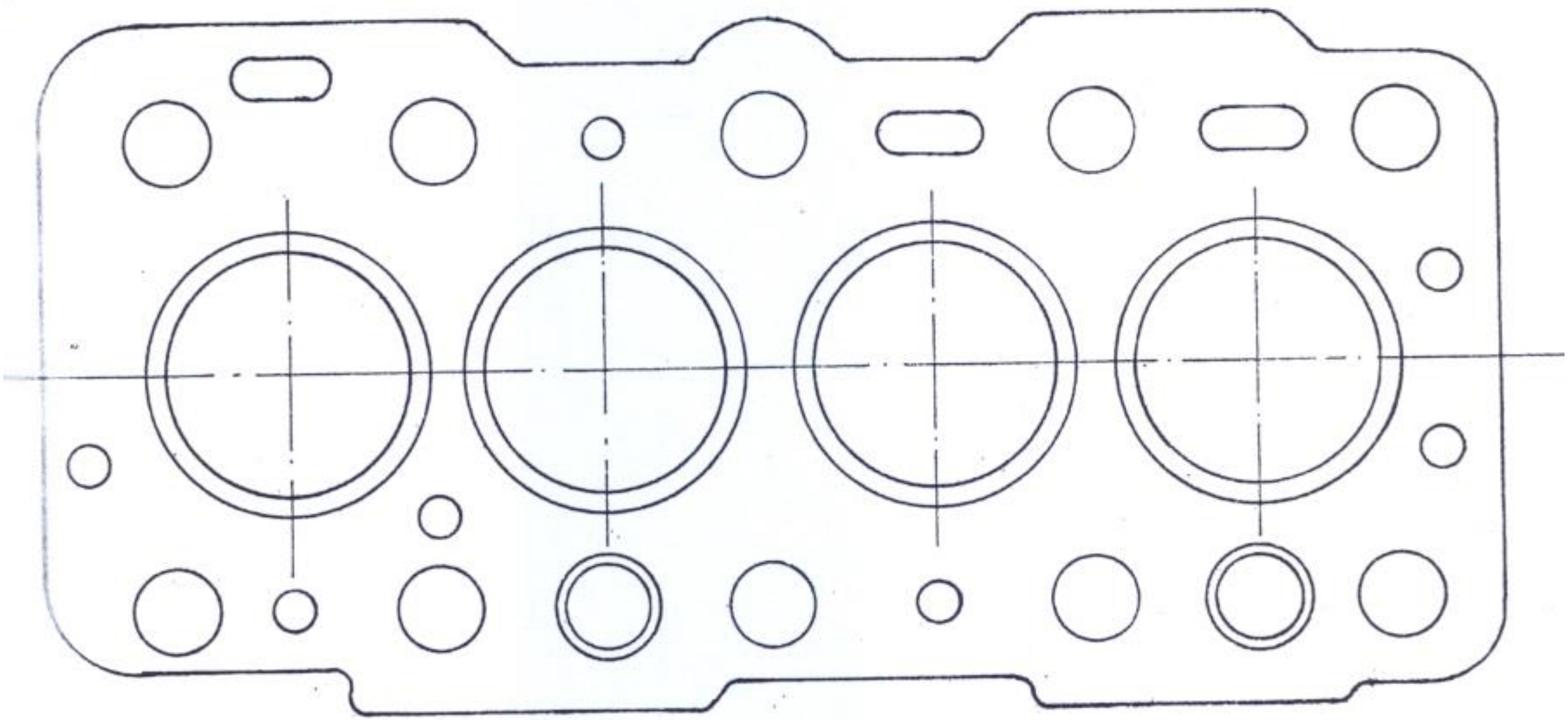
- Pistão
- Pino munhão
- Anéis de segmento
- Biela
- Árvore de manivela
- Volante
- Casquilho
- Válvula
- Mola de válvula
- Eixo comando de válvula

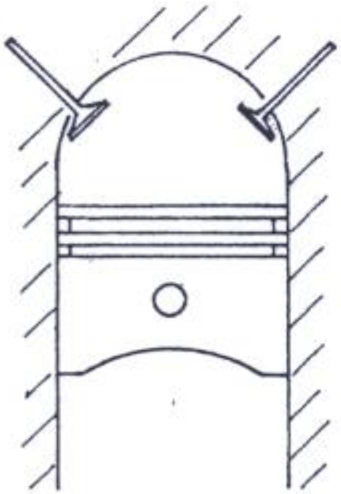


Cilindro fixo

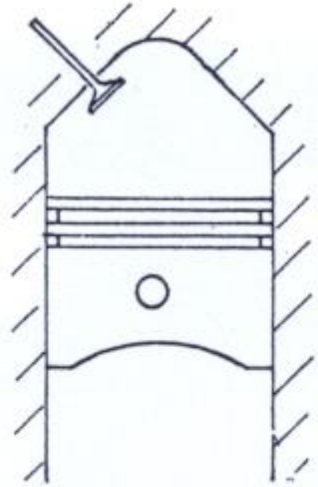


Cilindro com camisa
tipo substituivel a seco

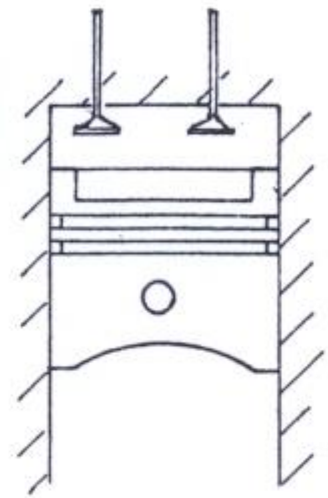




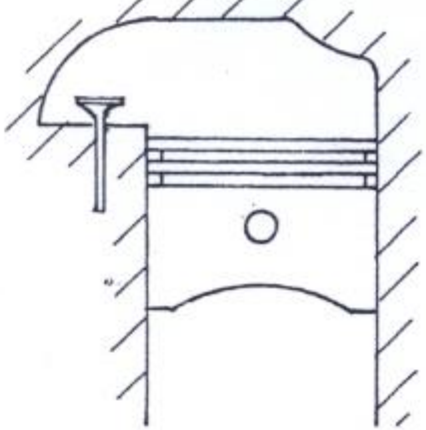
ESFÉRICA



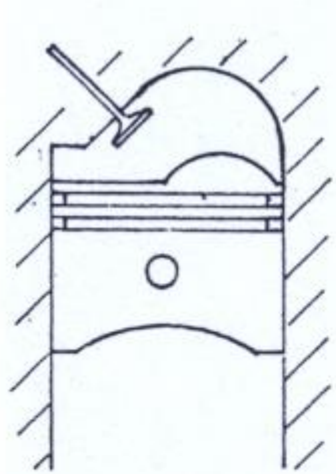
TRIANGULAR



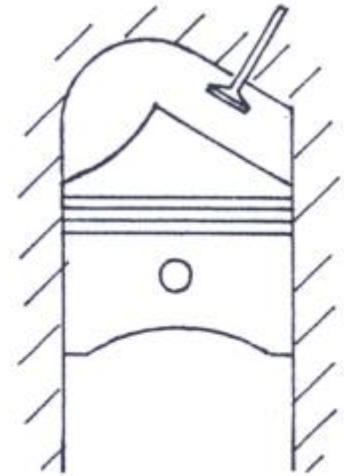
NO PISTÃO



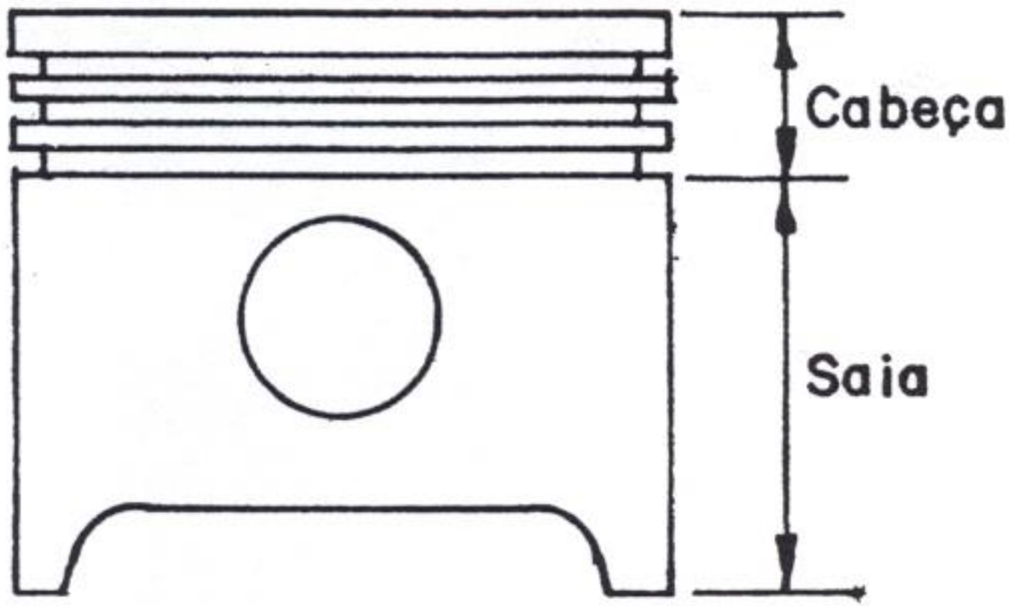
COM VÁLVULA LATERAL

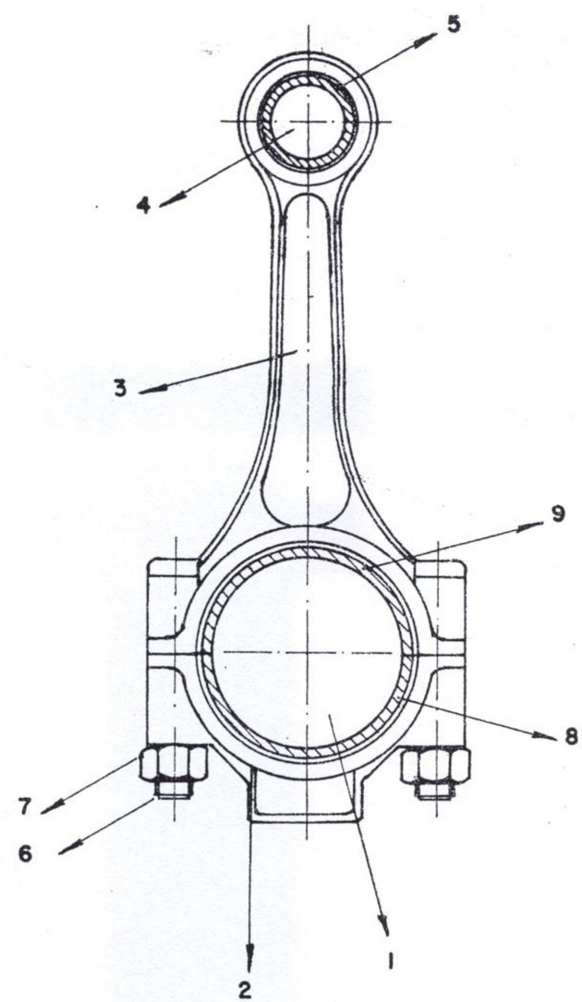


A BANHEIRA

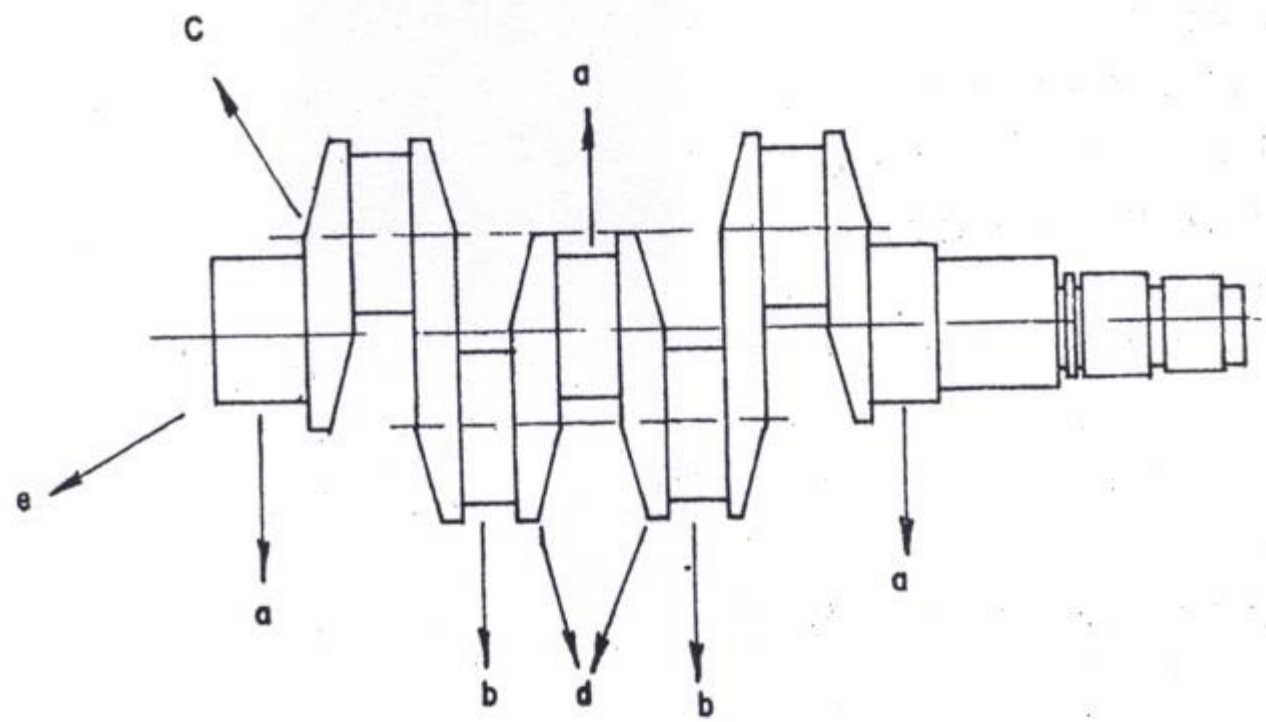


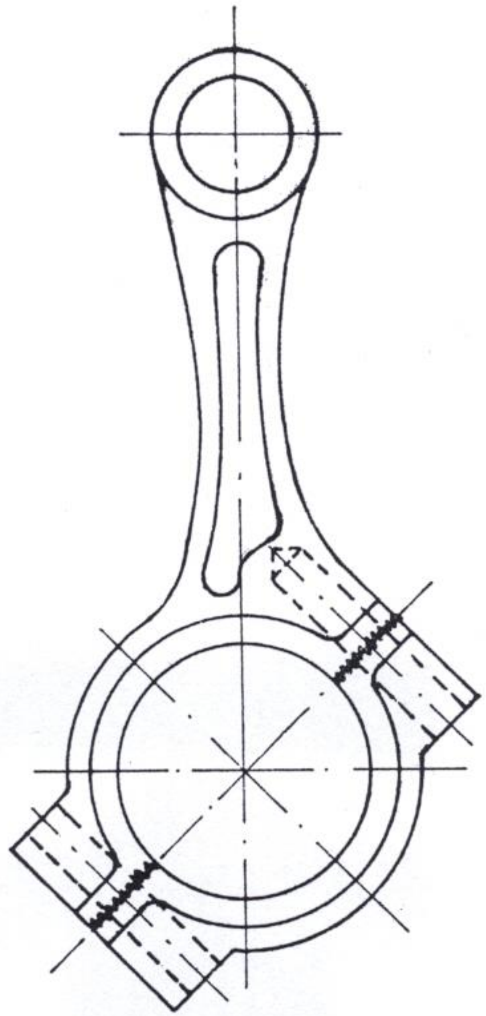
TRAPESOIDAL


Cabeça
Saia

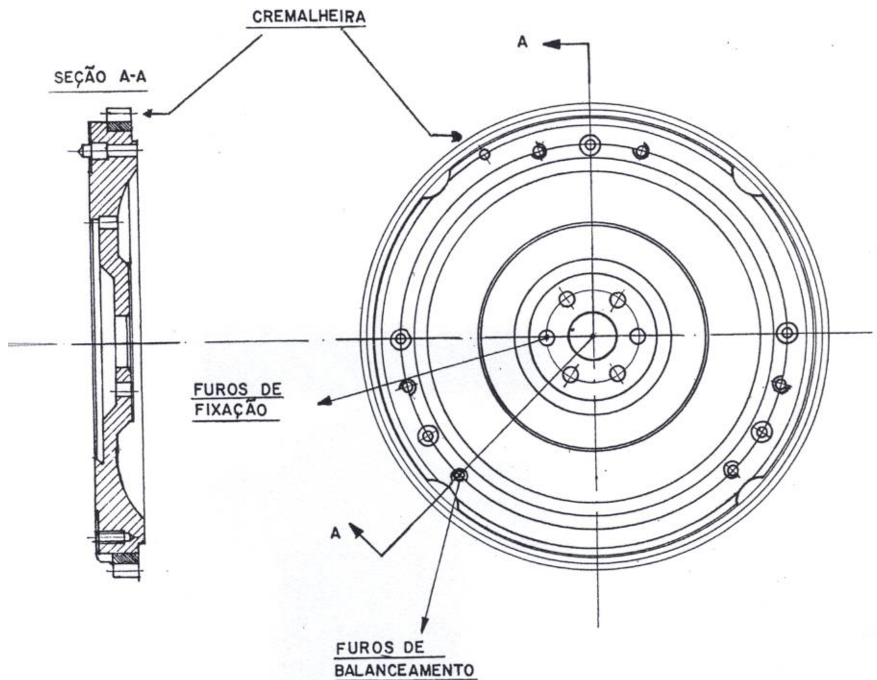


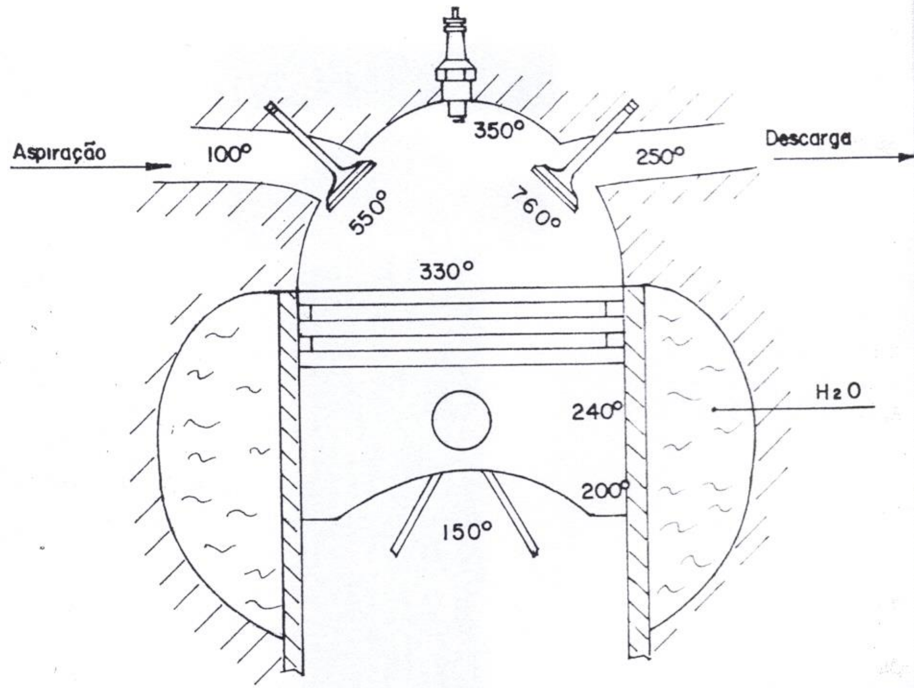
5
4
3
9
8
7
6
2
1


C
a
e
a
b
d
b
a

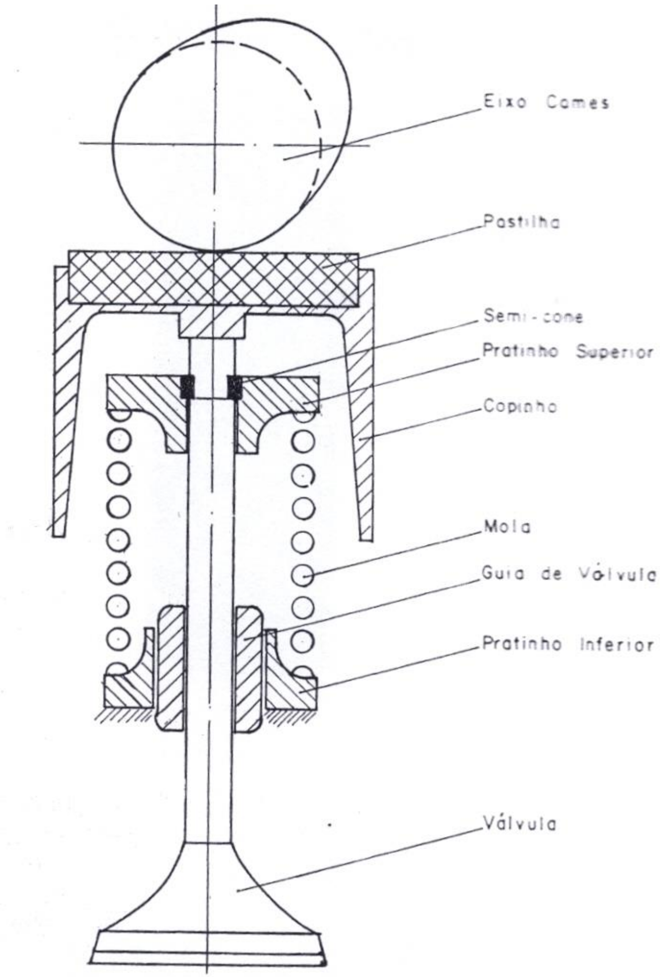


Árvore de manivela

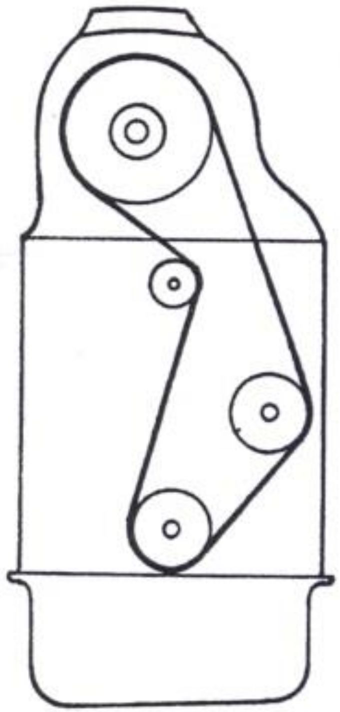

CREMALHEIRA
SEÇÃO A-A
A
FUROS DE
FIXAÇÃO
A
FUROS DE
BALANCEAMENTO



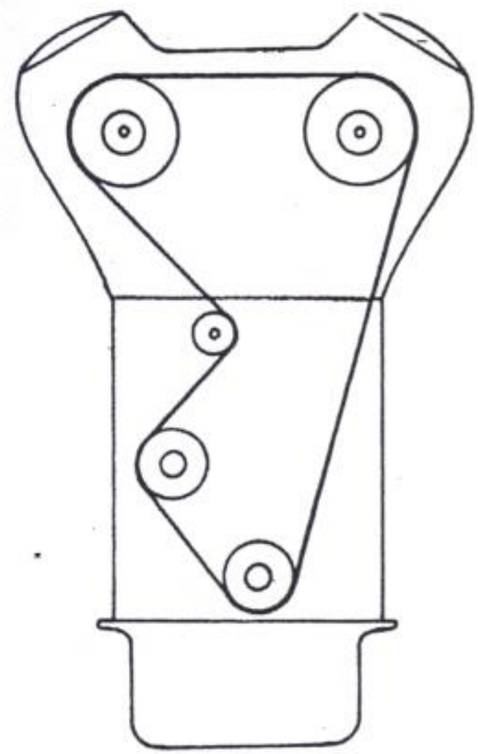
Aspiração
100°
350°
Descarga
250°
550°
760°
330°
H2O
240°
200°
150°



Eixo Cames
Pastilha
Semi-cone
Pratinho Superior
Copinho
Mola
Guia de Válvula
Pratinho Inferior
Válvula



COMANDO SIMPLES



COMANDO DUPLO

ꞁTORES

4. MOVIMENTO DO CILINDRO

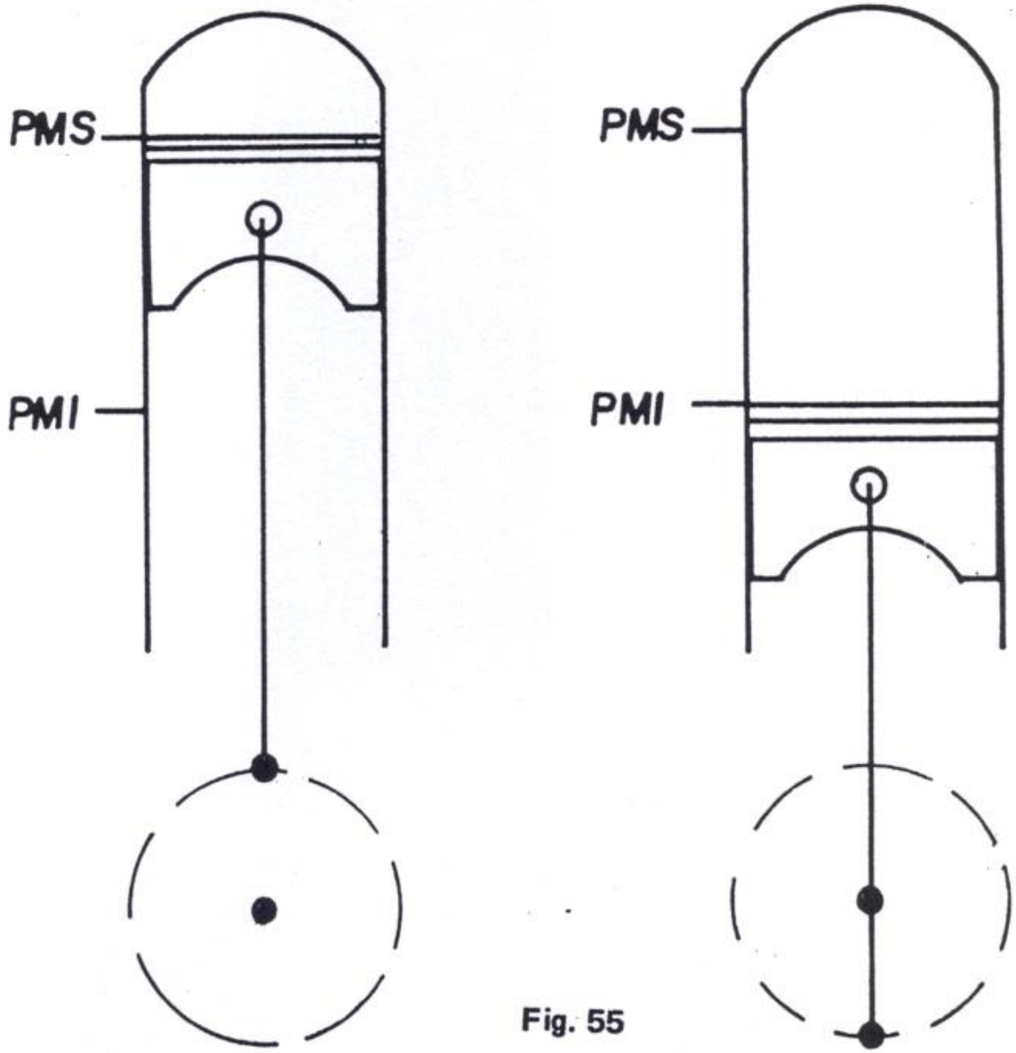


Fig. 55

5. DEFINIÇÕES

6. CICLOS OPERATIVOS

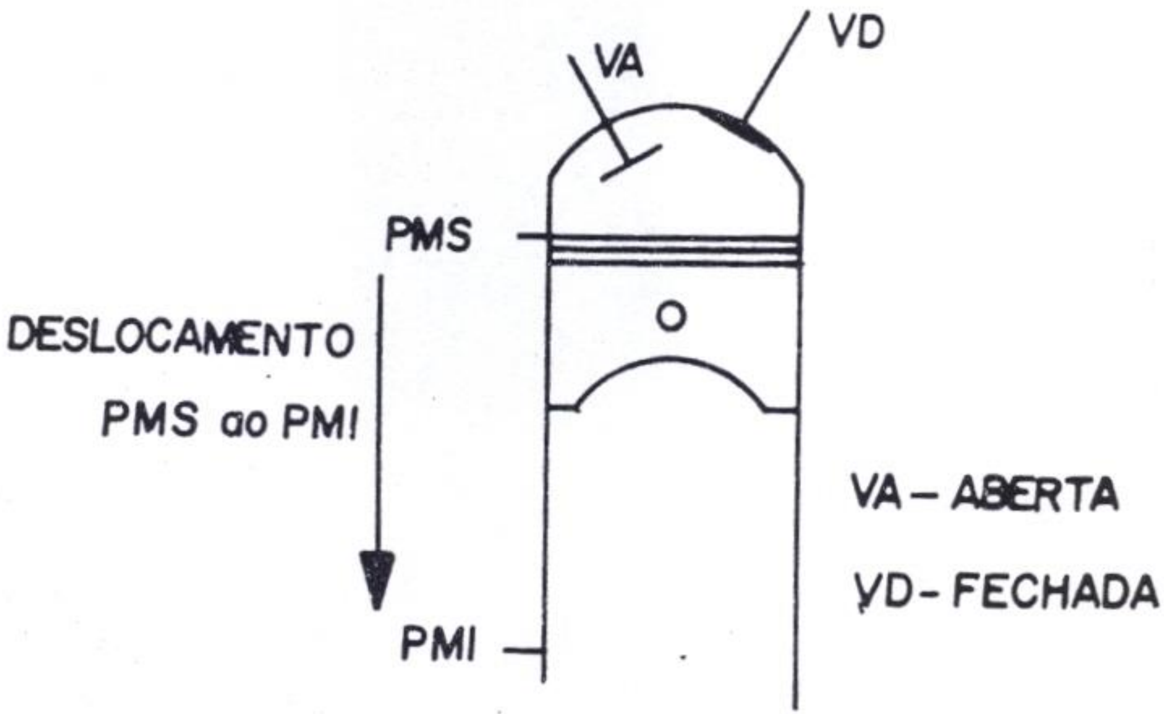


Fig. 59

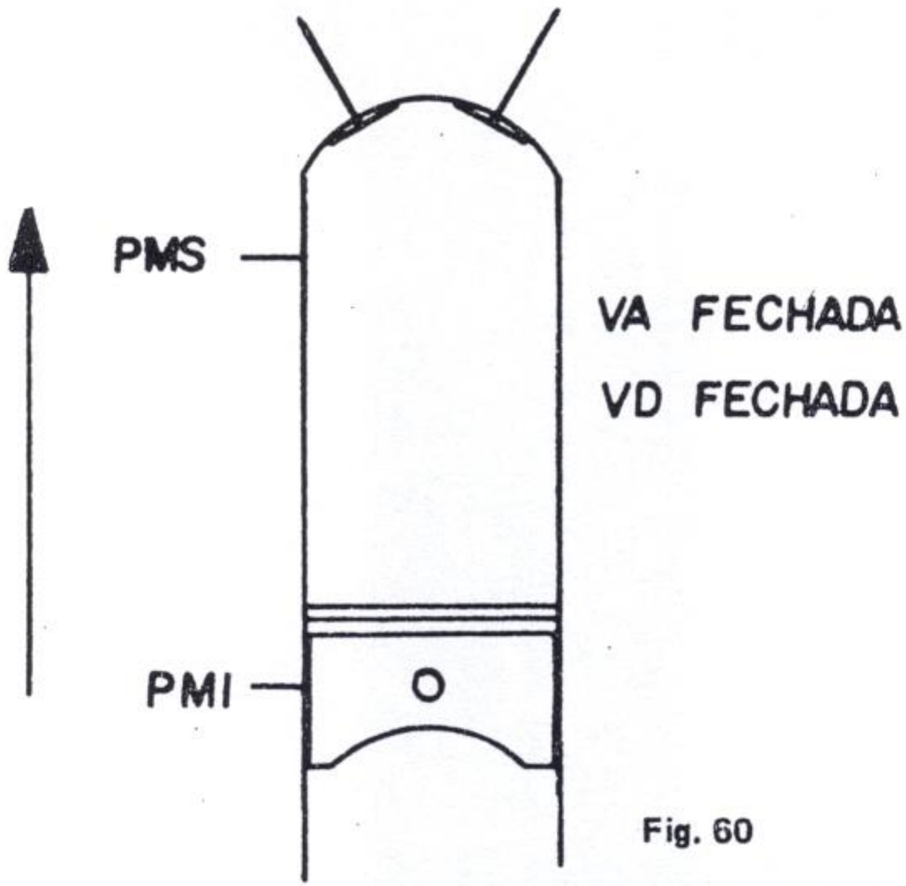


Fig. 60

3º TEMPO: COMBUSTÃO (EXPANSÃO)

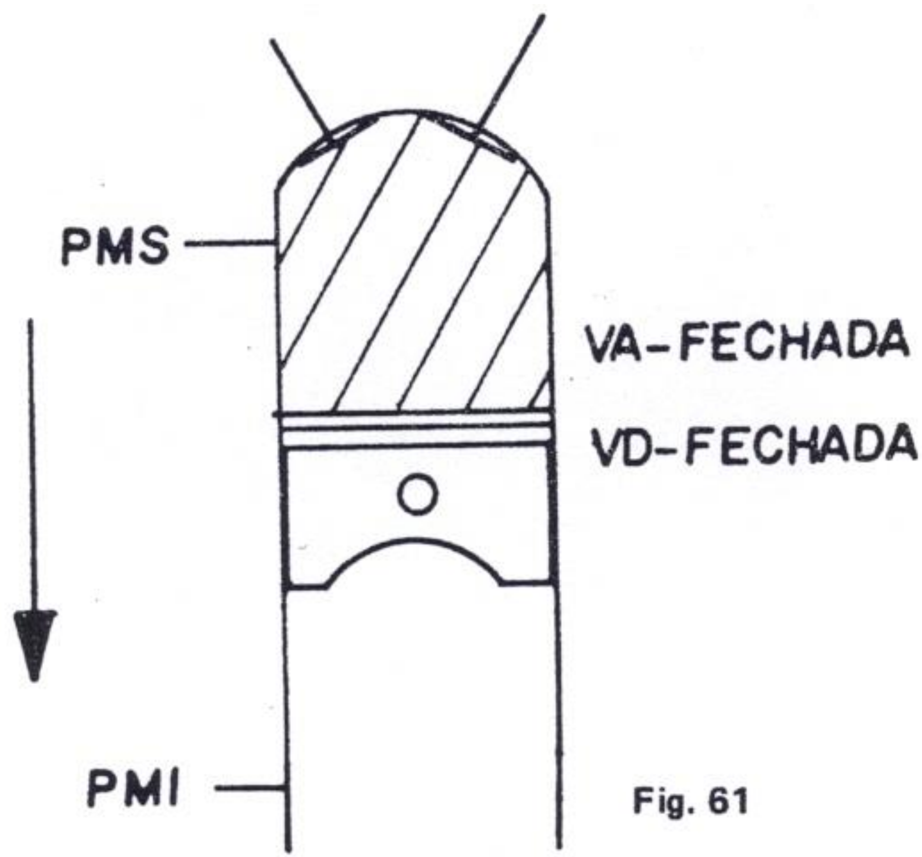


Fig. 61

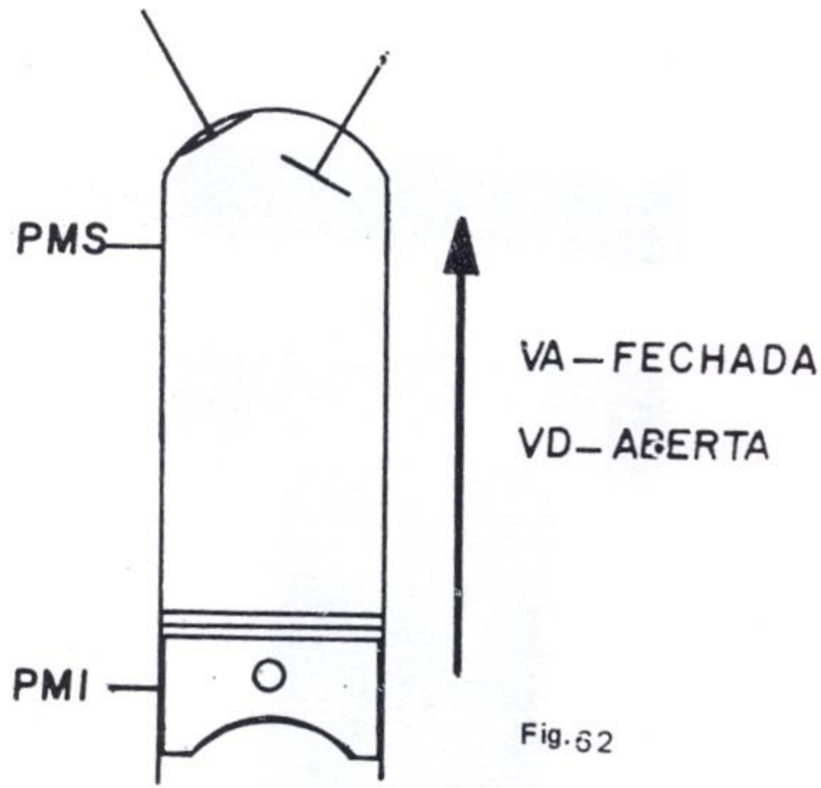
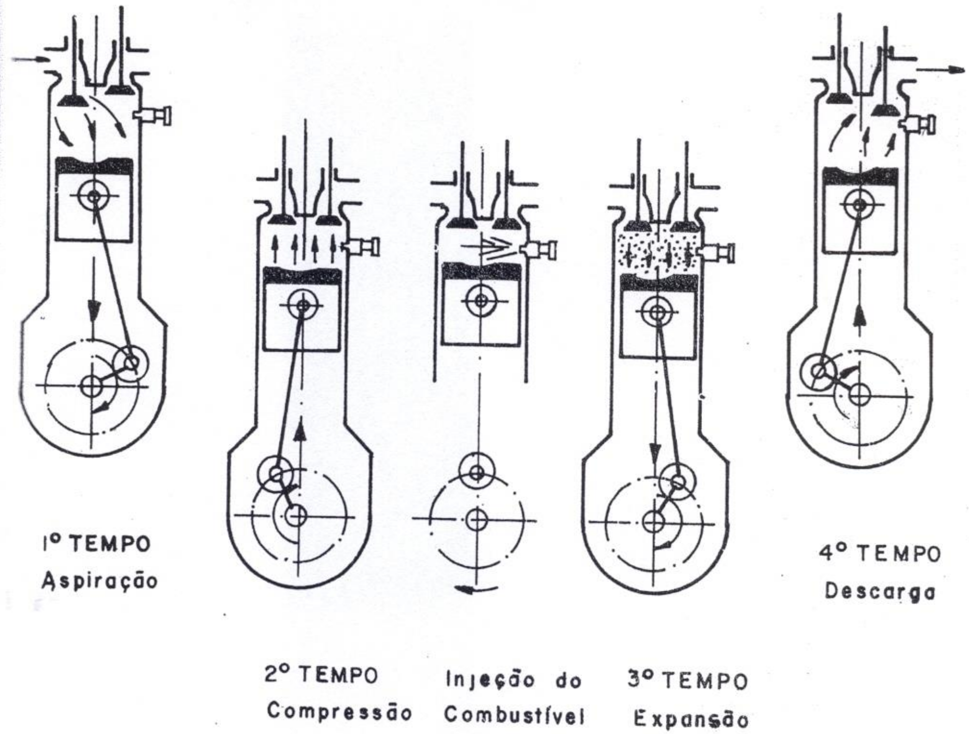
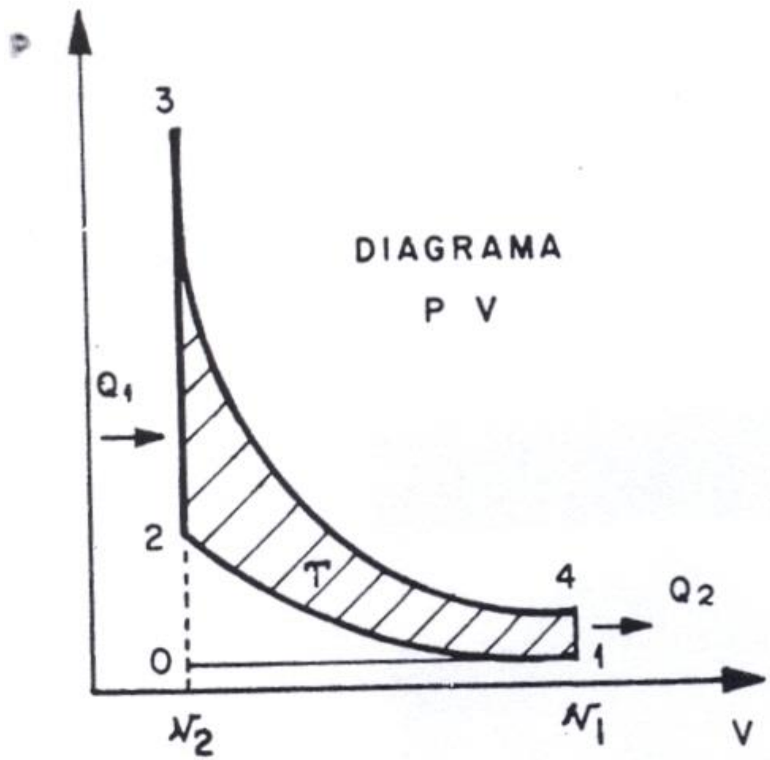


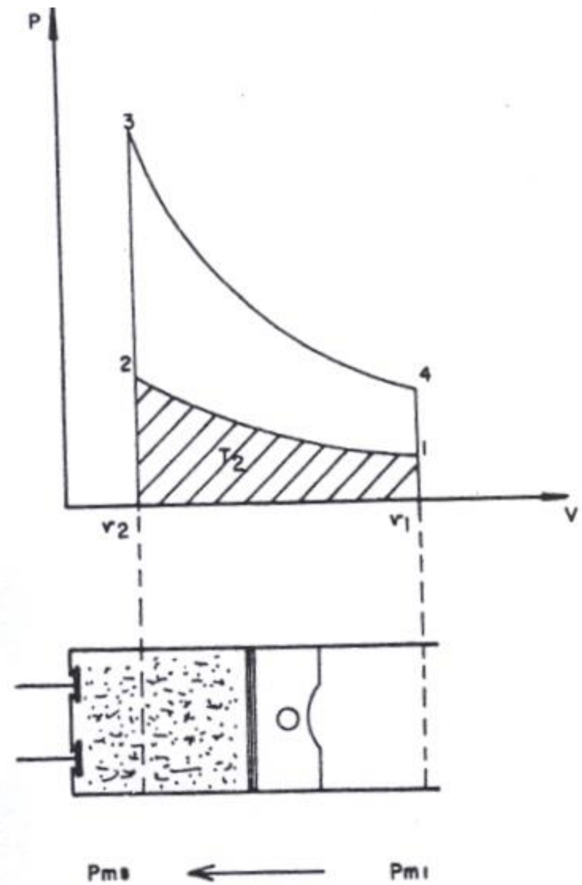
Fig. 62


1º TEMPO
Aspiração
2º TEMPO
Compressão
Injeção do
Combustível
3º TEMPO
Expansão
4º TEMPO
Descarga

7. ASPECTOS DE TERMODINÂMICA



P
3
DIAGRAMA
P V
Q1
2
T
4
Q2
0
1
v2
v1
V



P
3
2
4
T2
1
V
v2
v1
Pms
Pmi

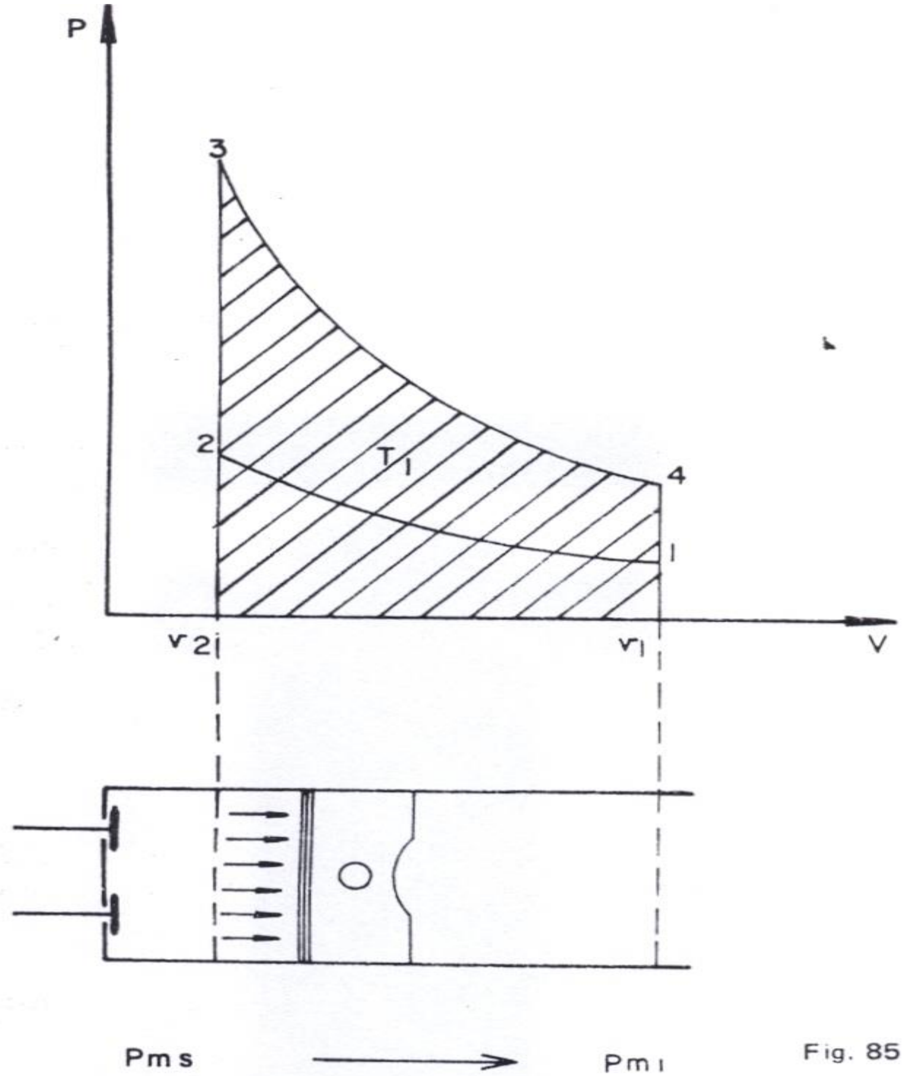


Fig. 85

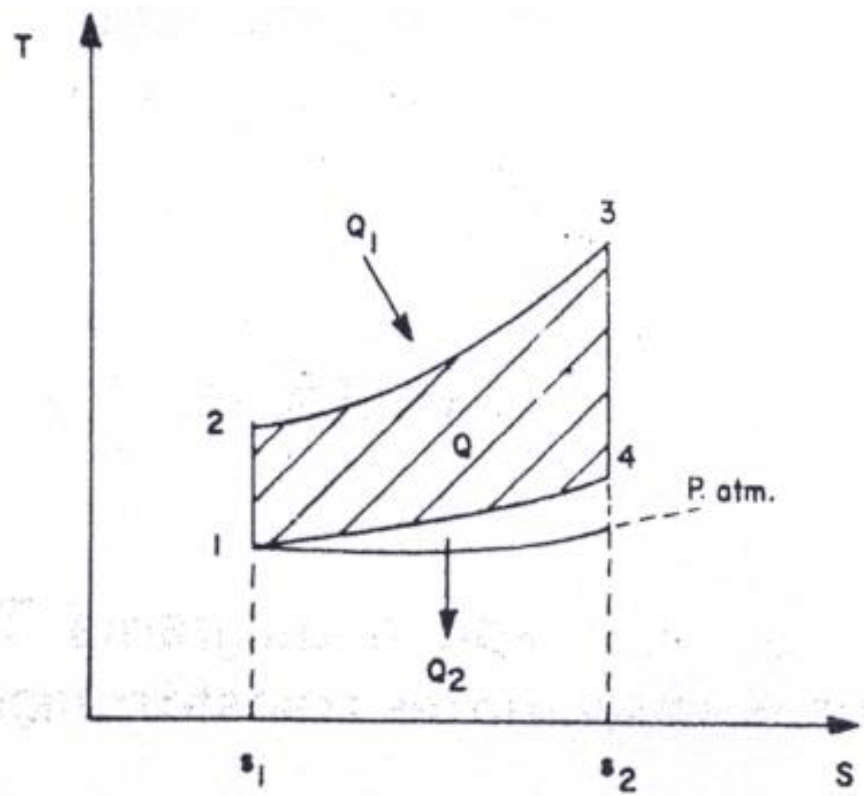


Fig. 86

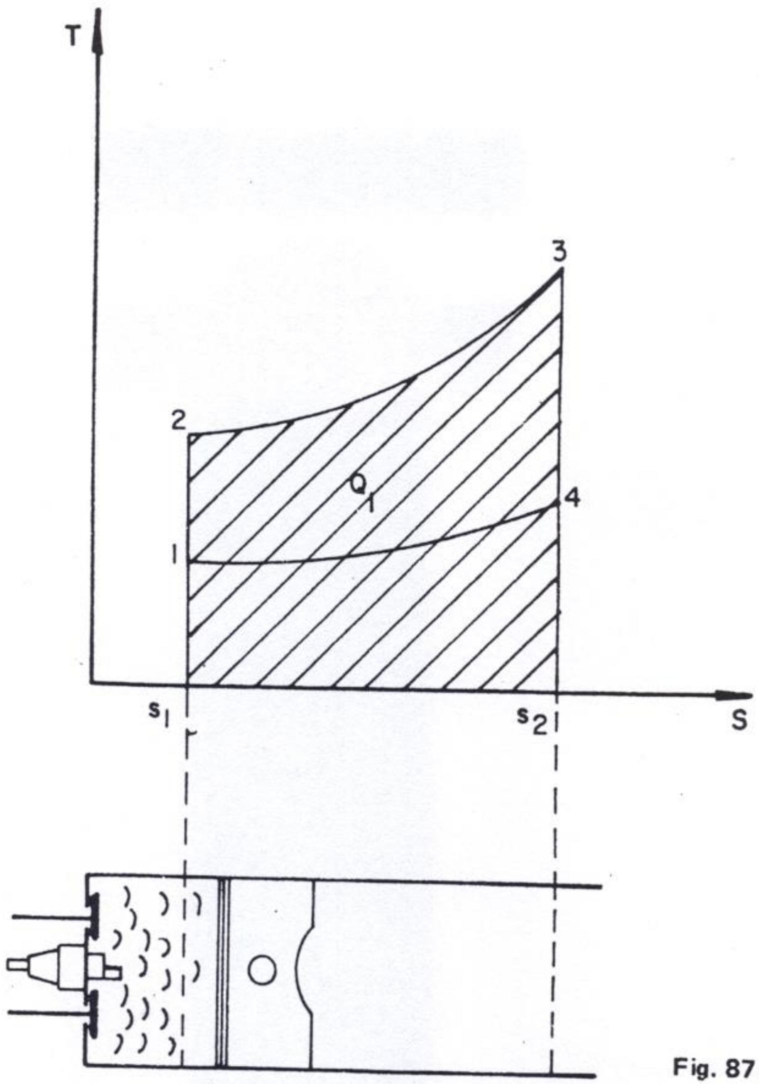
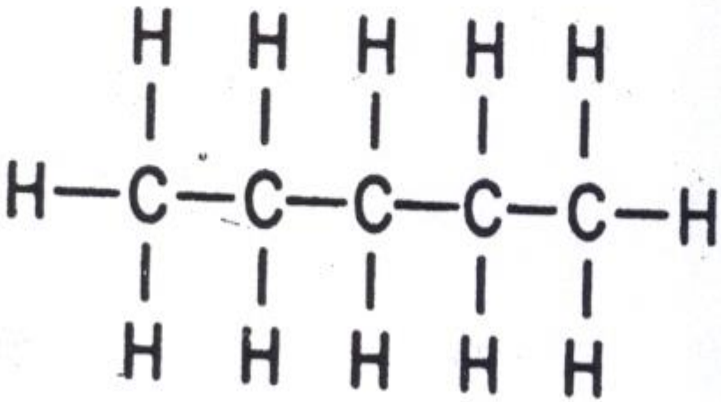
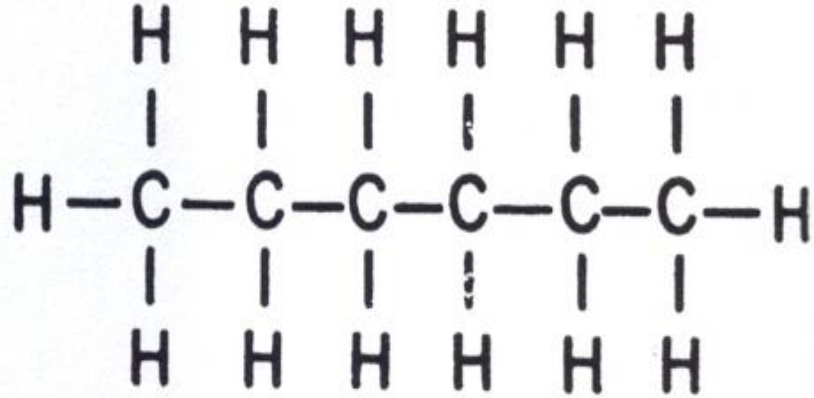


Fig. 87 a

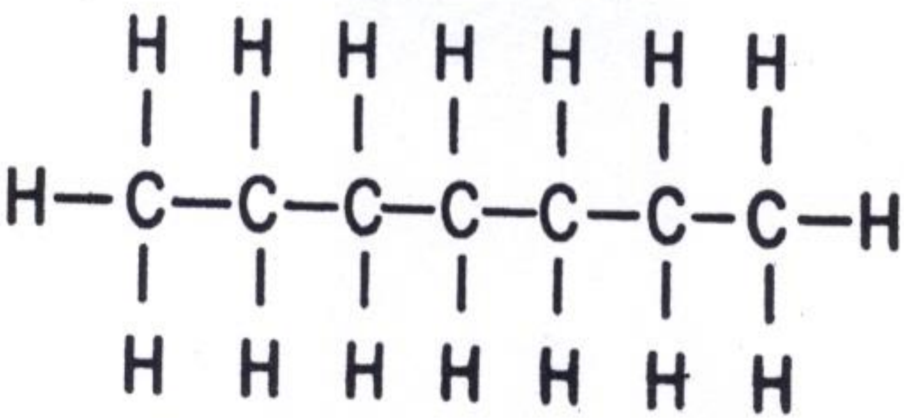
8. COMBUSTÌVEL



PENTANO



HEXANO



HEPTANO

Fig. 115

COMBUSTÍVEL	TÍTULO ESTEQUIOMÉTRICO	COMBUSTÍVEL	TÍTULO ESTEQUIOMÉTRICO
ciclopentano	14,7	hidrogênio	29,6
ciclohexano	14,7	monóxido carbono	29,6
benzina	13,2	metano	9,5
tolueno	13,4	etano	5,7
xileno	13,6	propano	4
propeno	14,7	butano	3,1
buteno	14,7	benzol	2,7
penteno	14,7		
hexeno	14,7		
hepteno	14,7		
hexadecano	14,7		
metanol	6,4		
etanol	9,0		
propanol	10,5		
butanol	11,1		

Fig. 126

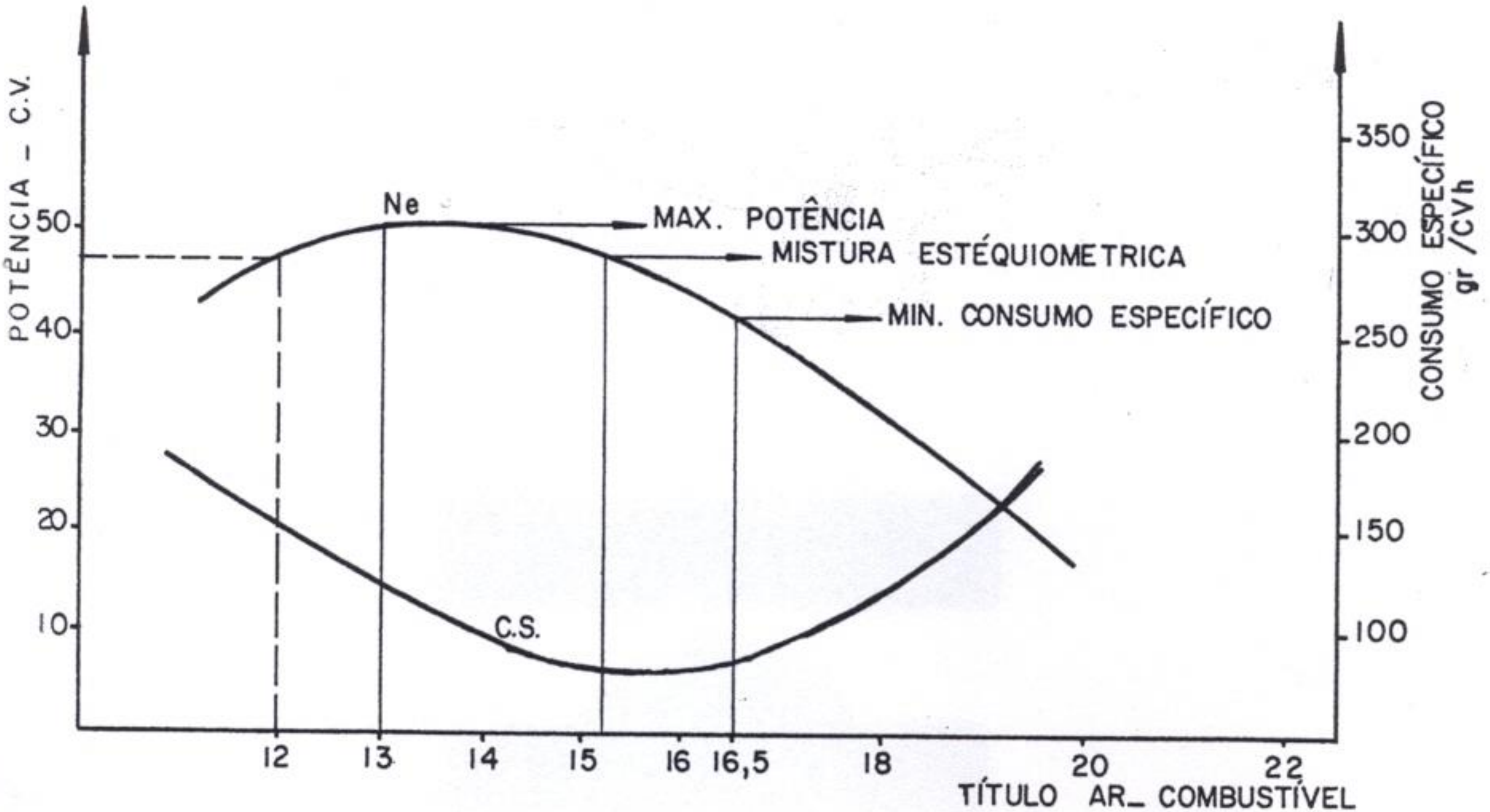
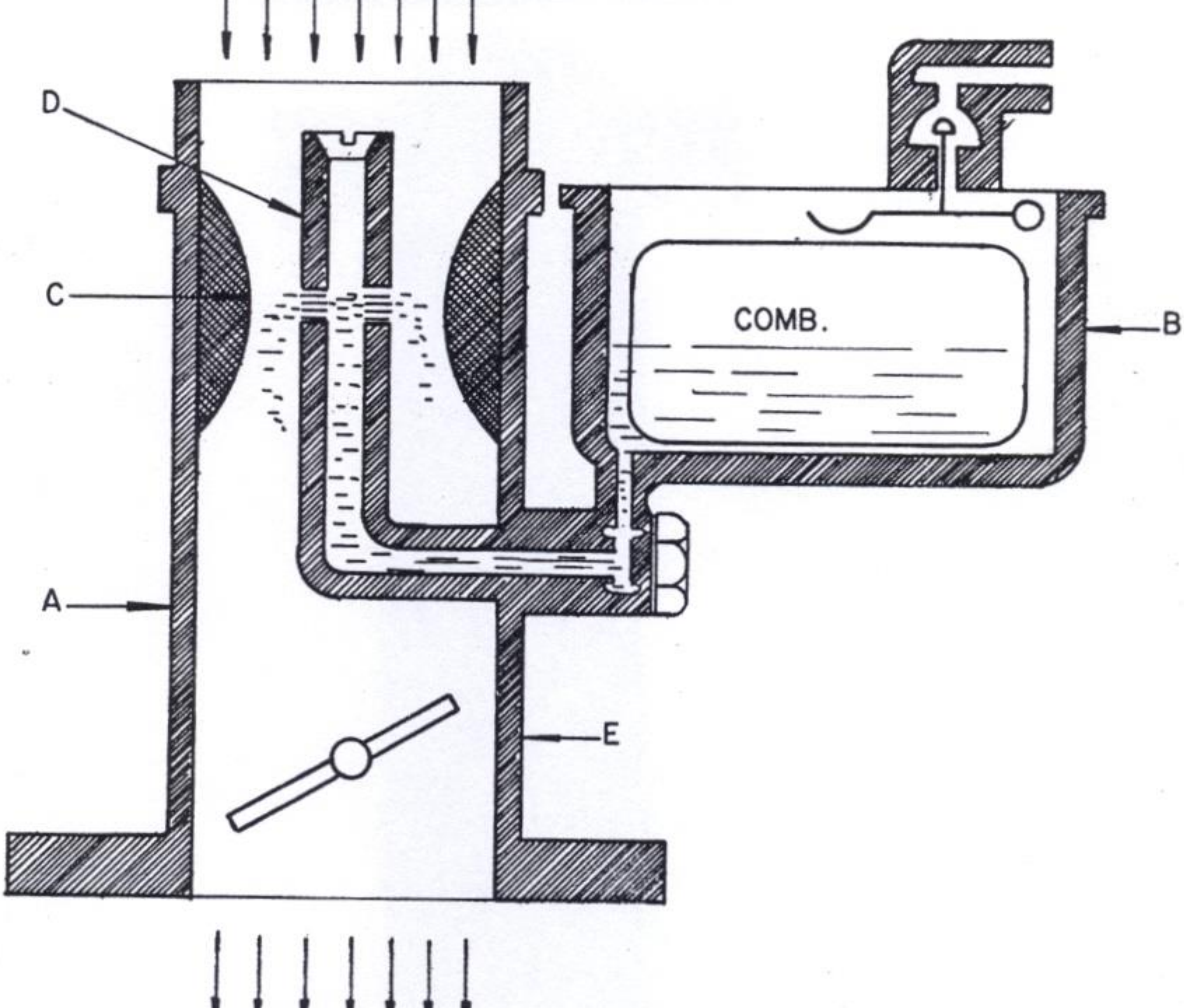
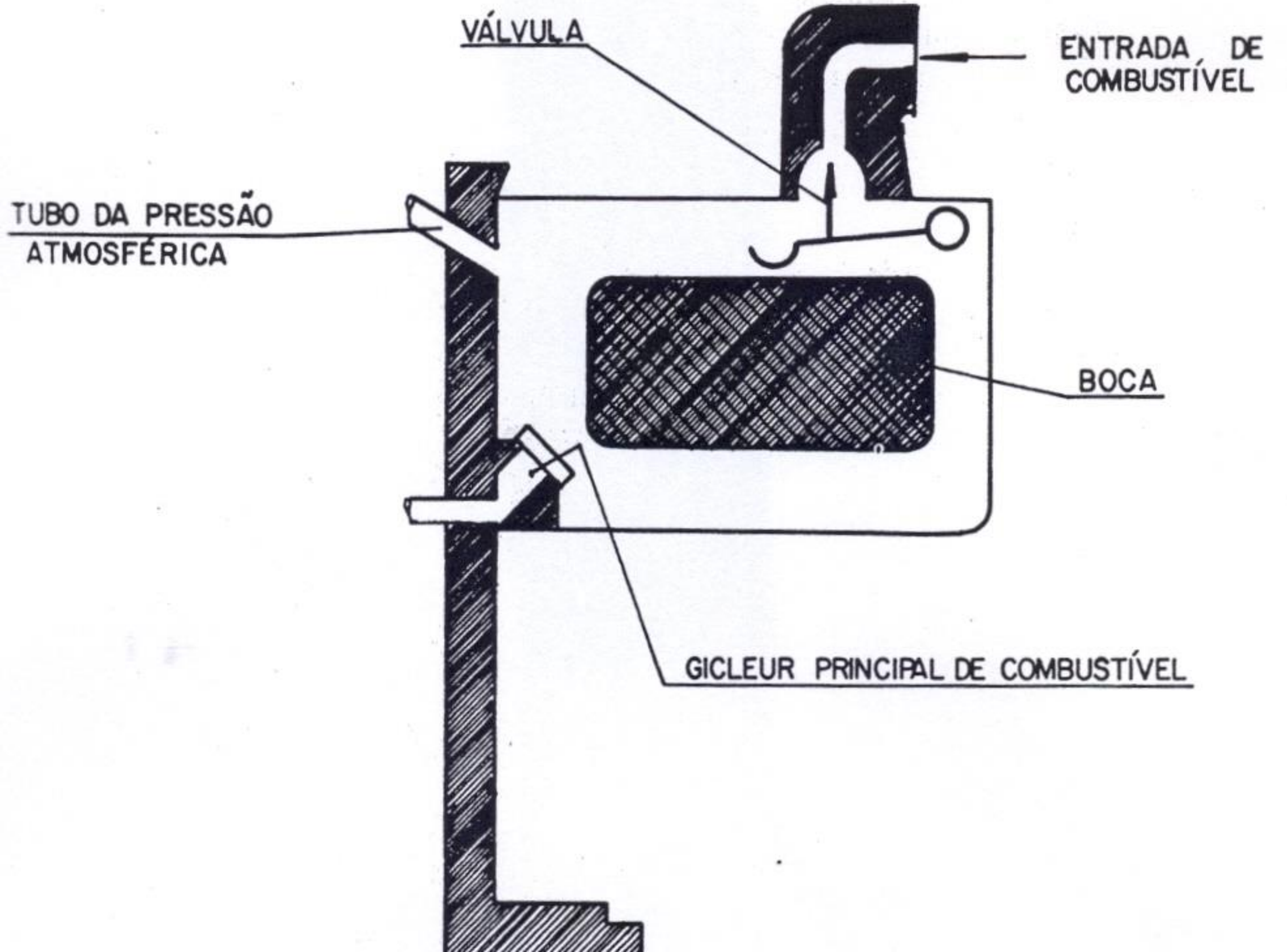

POTÊNCIA - C.V.
50
40
30
20
10
Ne
MAX. POTÊNCIA
MISTURA ESTÉQUIOMETRICA
MIN. CONSUMO ESPECÍFICO
C.S.
350
300
250
200
150
100
CONSUMO ESPECÍFICO gr /CVh
12
13
14
15
16
16,5
18
20
22
TÍTULO AR_ COMBUSTÍVEL

Fig. 127

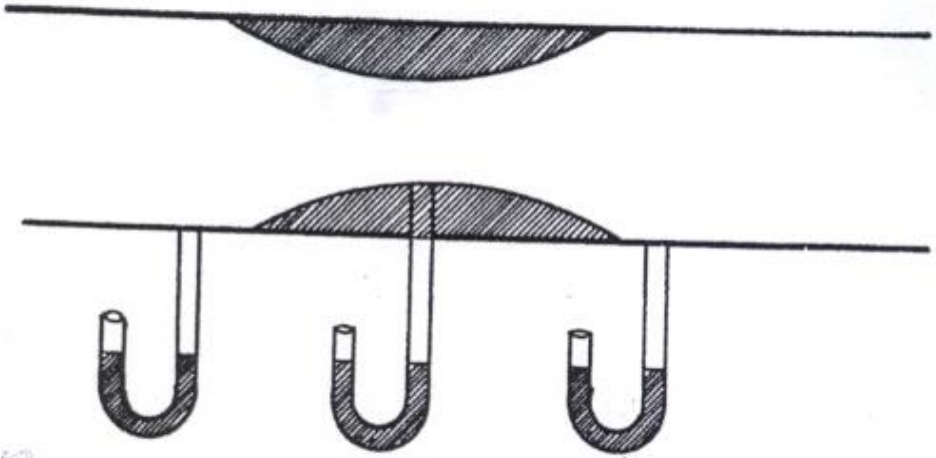
8. CARBURADOR


D
C
A
COMB.
B
E



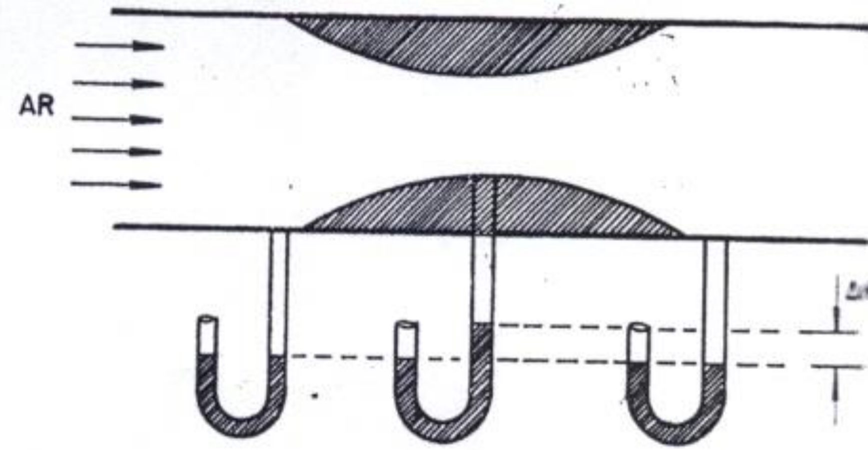
VÁLVULA
ENTRADA DE COMBUSTÍVEL
TUBO DA PRESSÃO ATMOSFÉRICA
BOCA
GICLEUR PRINCIPAL DE COMBUSTÍVEL

Fig. 134



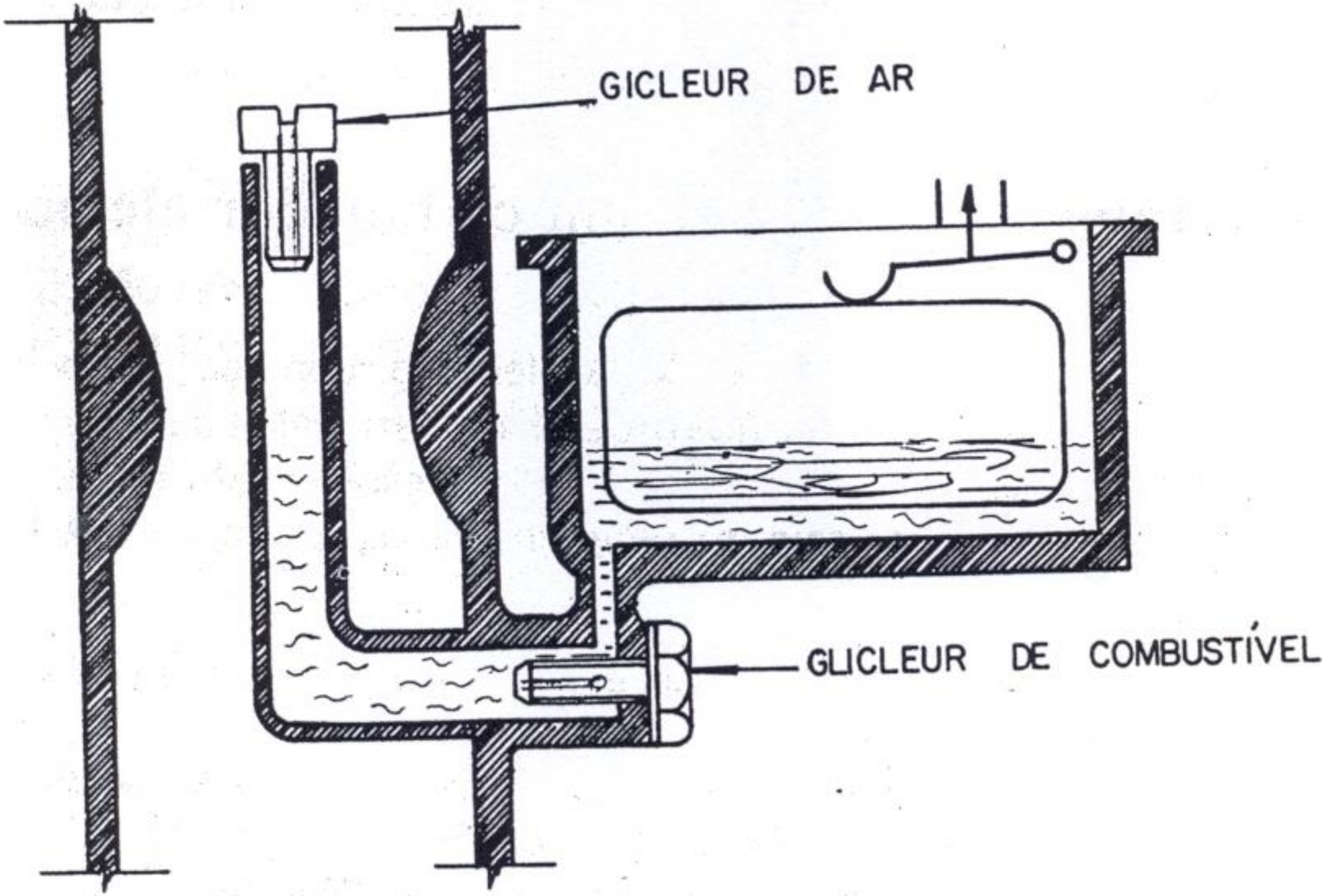
SEM FLUXO DE AR

Fig. 135

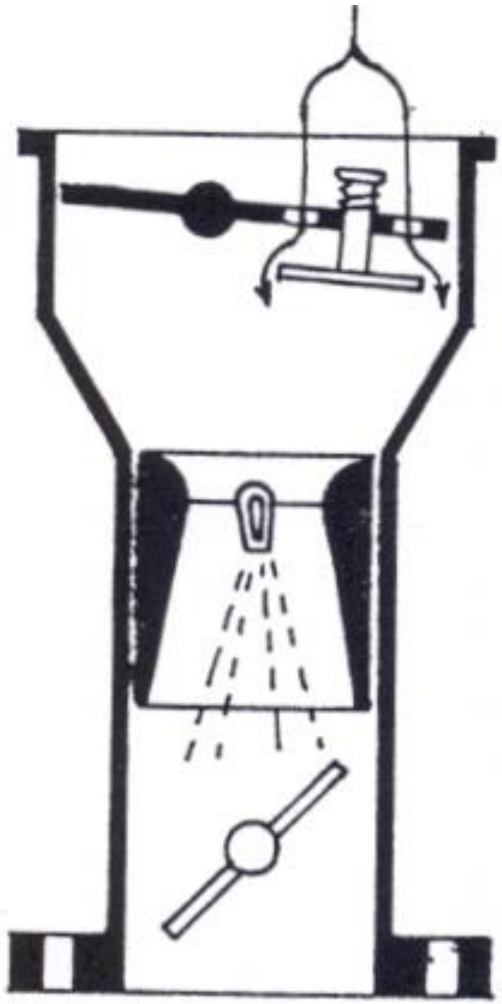


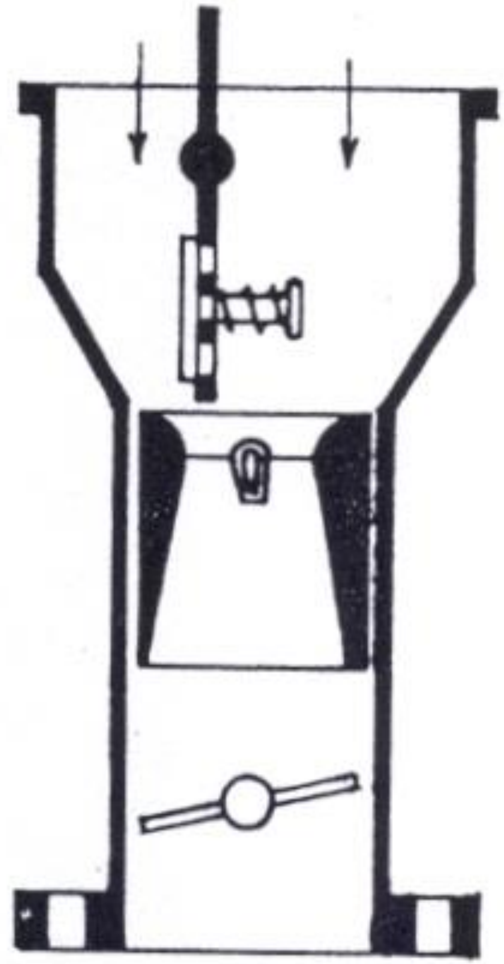
COM FLUXO DE AR

Fig. 136


GICLEUR DE AR
GLICLEUR DE COMBUSTÍVEL

PARTIDA





ACELERAÇÂO

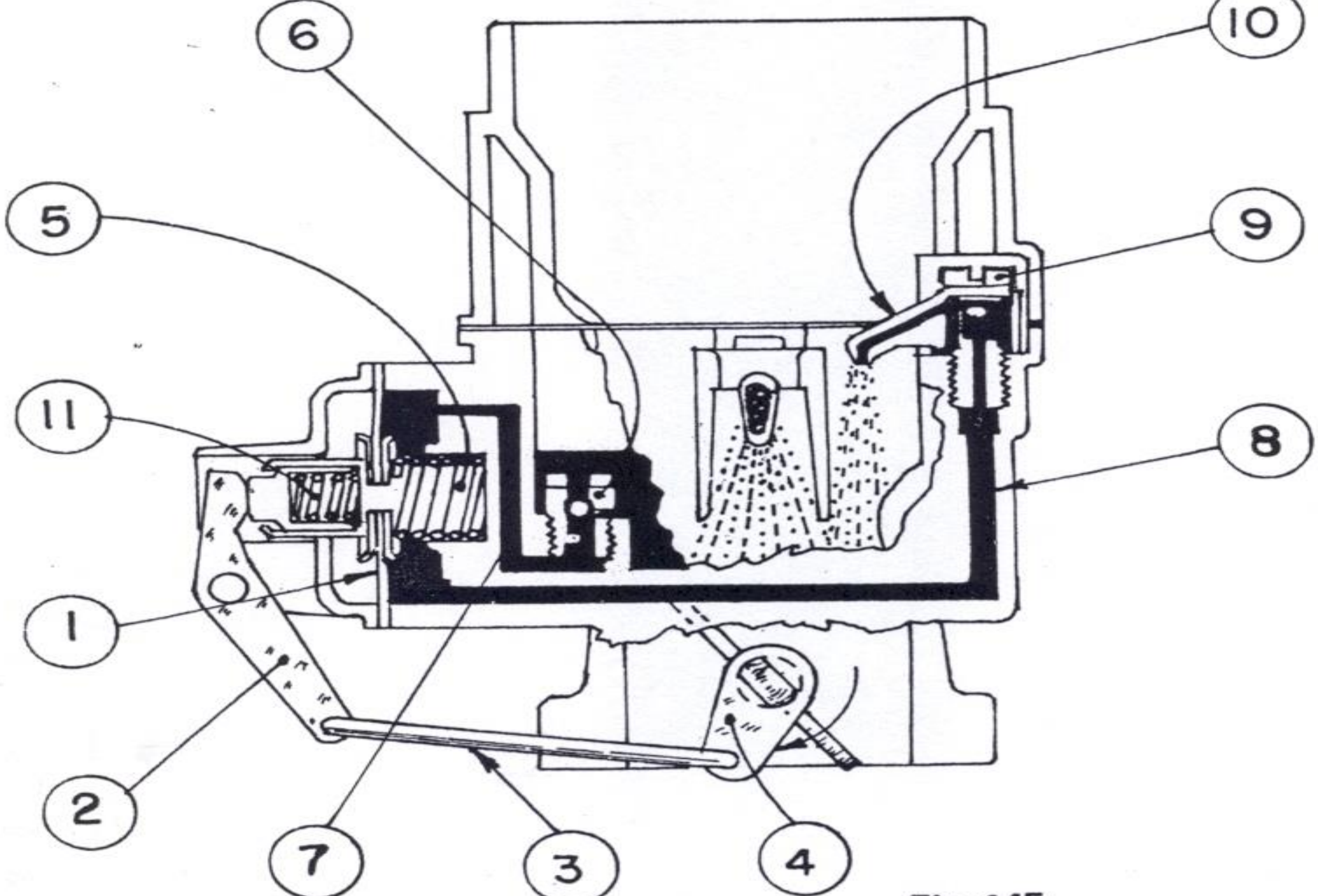
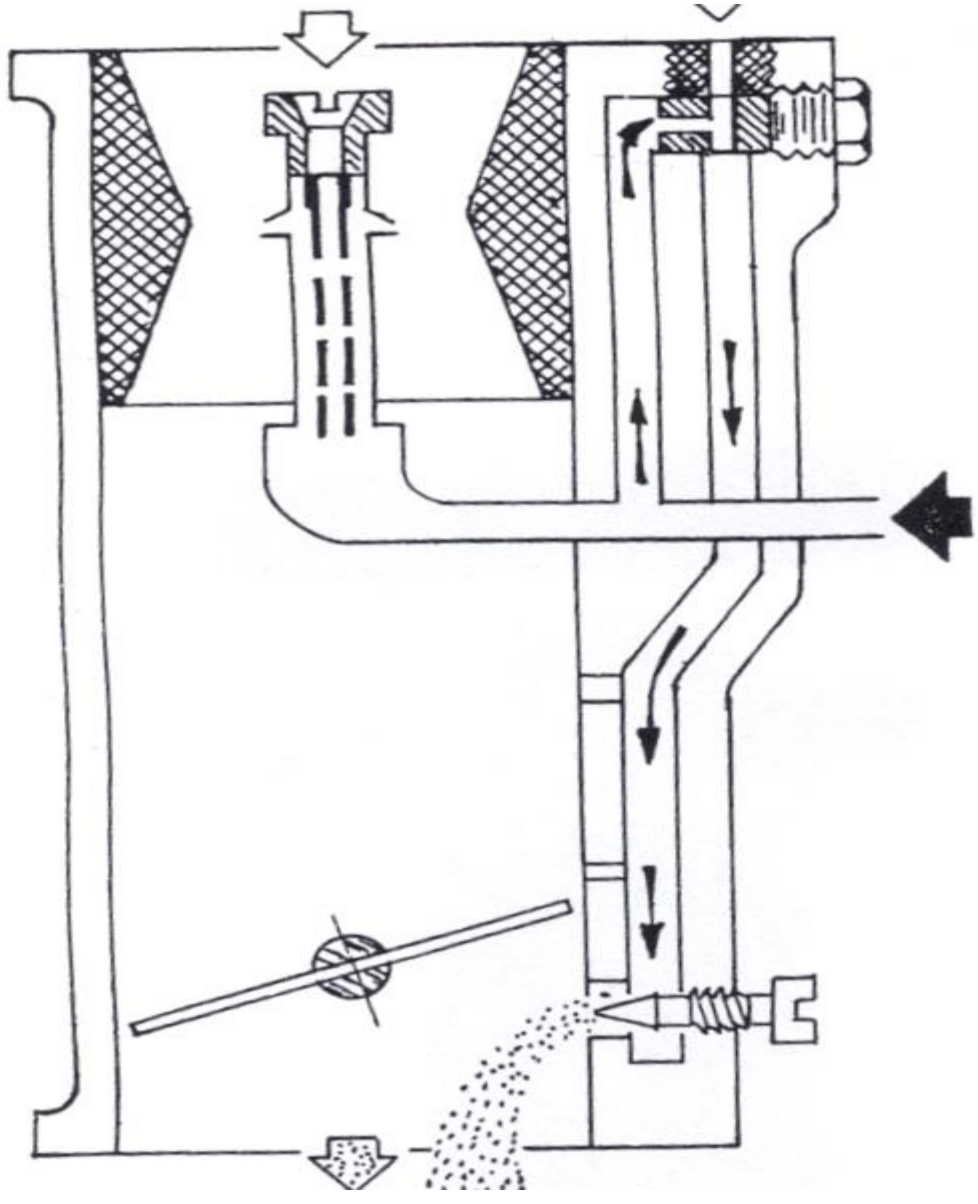


Fig. 145

MARCHA LENTA



F

PROGRESSÂO DE ACELERACÂO

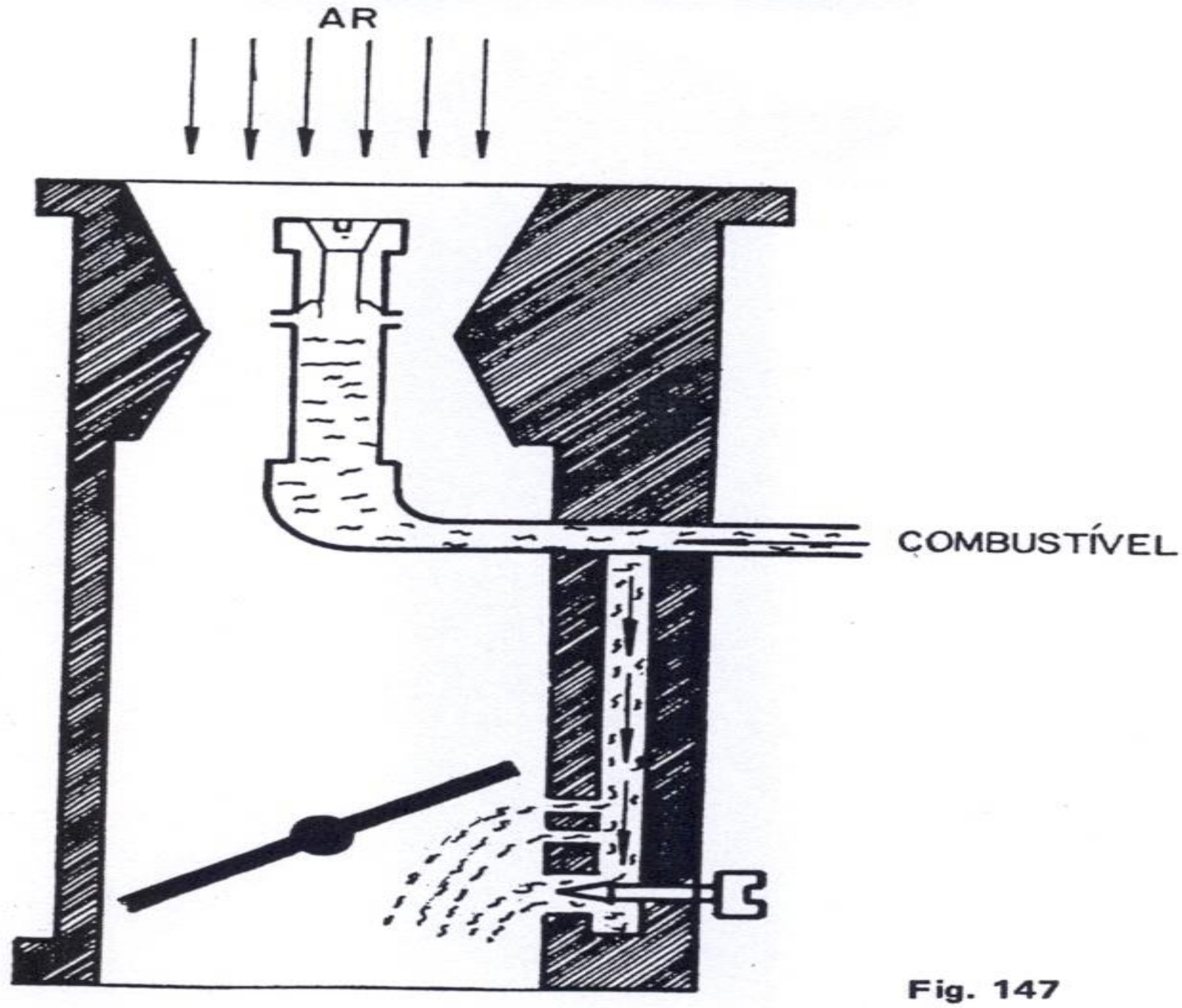


Fig. 147

CIRCUITO SUPLEMENTAR DE POTÊNCIA

a mistura.

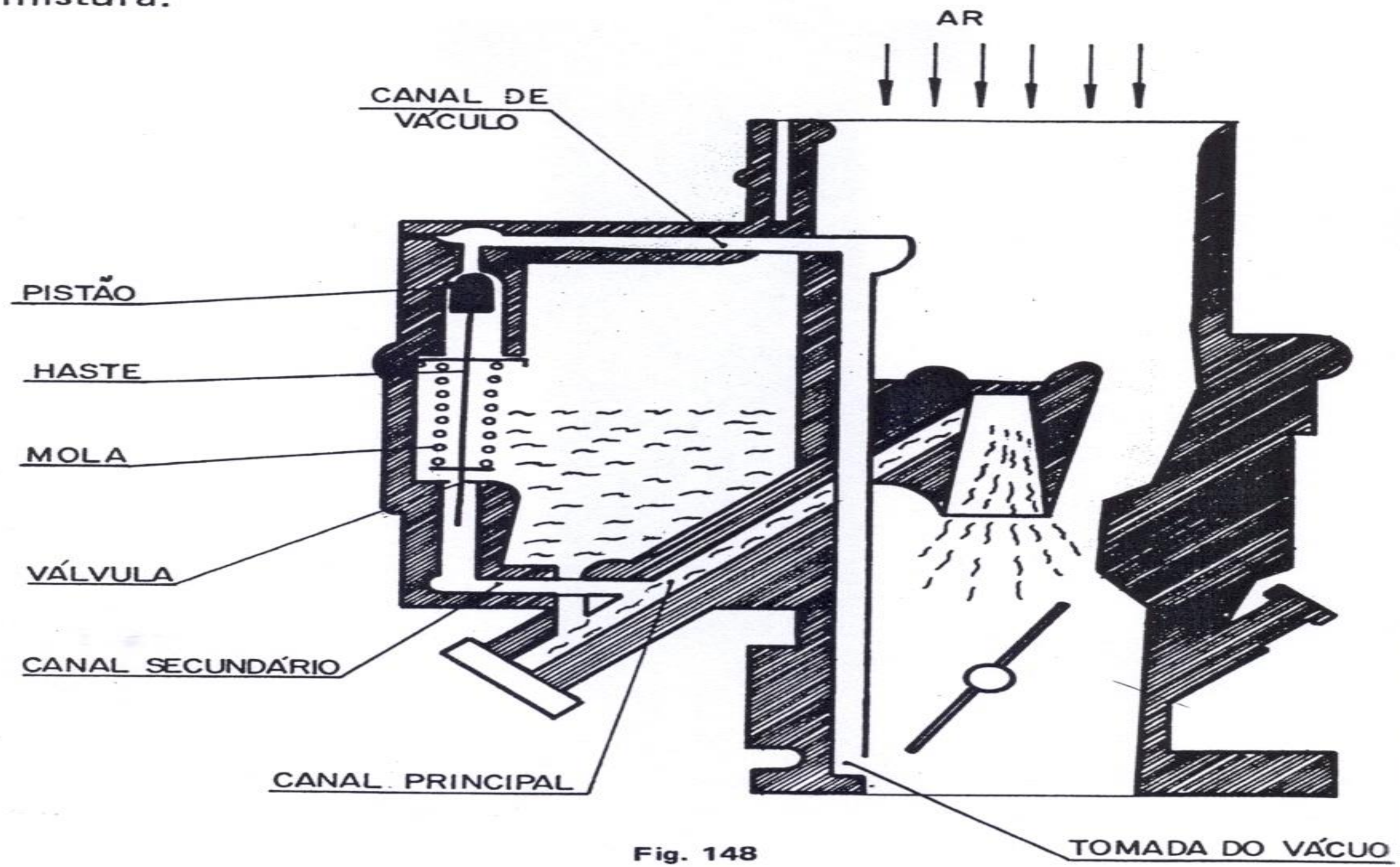
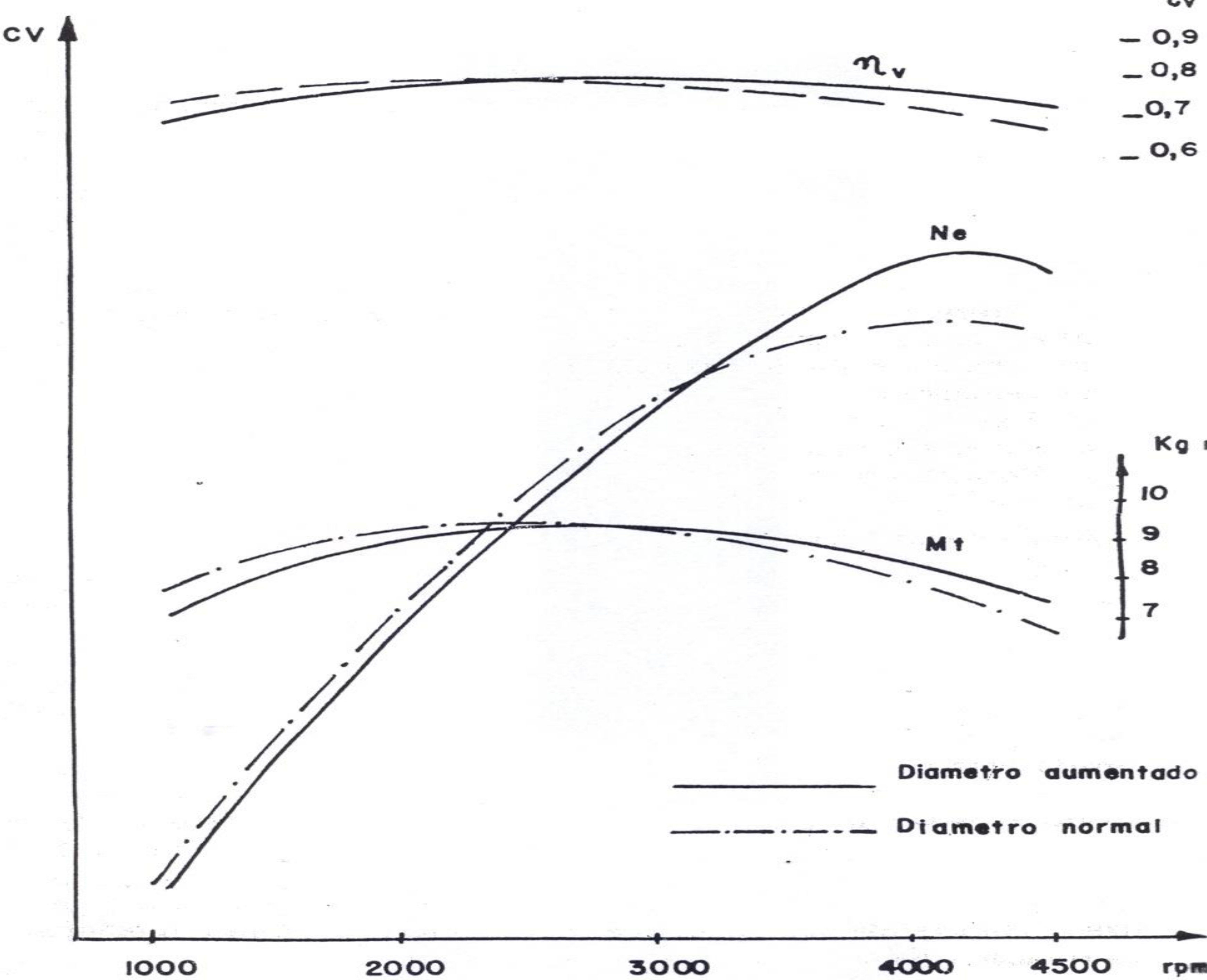


Fig. 148


CV
CV
0,9
0,8
0,7
0,6
η_v
Ne
Kg m
10
9
8
7
Mt
Diametro aumentado
Diametro normal
1000
2000
3000
4000
4500
rpm

TERMODINÃMICA

2. *THERMODYNAMIC ENGINE CYCLES*

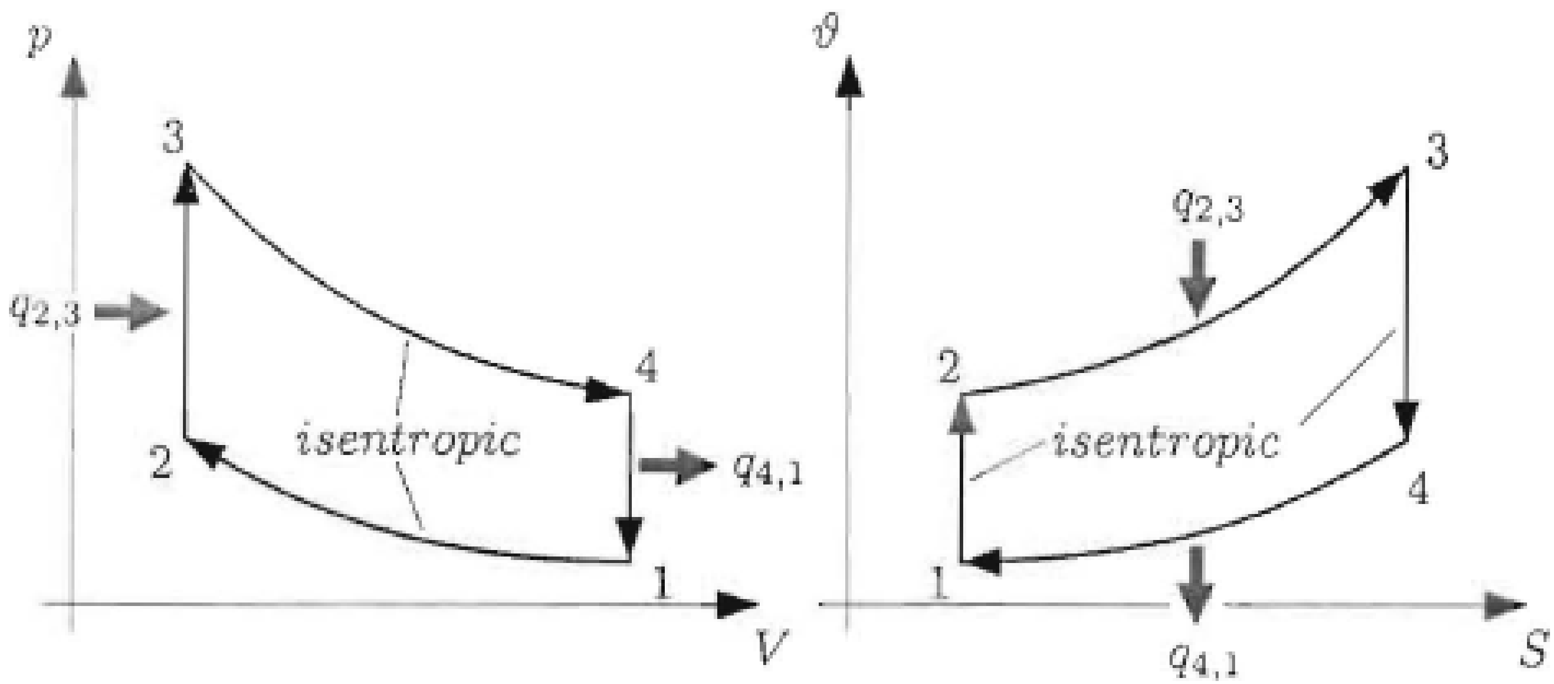


Figure 2.1 pV-diagram (left) and ϑS-diagram (right) of the SI engine process

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

$1 \rightarrow 2$: Isentropic compression, $dq = 0$:

$$
\begin{aligned}
dq &= du + dw = 0 \\
q_{1,2} &= 0 \\
dw &= -du = -m\, c_v\, d\vartheta \\
w_{1,2} &= -\int_1^2 m\, c_v\, d\vartheta = -m\, c_v(\vartheta_2 - \vartheta_1)
\end{aligned}
$$

The work $w_{1,2}$ is used to compress the gas and therefore, it is negative.

$2 \rightarrow 3$: Isochoric input of thermal energy, $dV = 0$:

$$\begin{aligned} dw &= p\,dV = 0 \\ w_{2,3} &= \int_2^3 p\,dV = 0 \\ dq &= du = m\,c_v\,d\vartheta \\ q_{2,3} &= m\,c_v \int_2^3 d\vartheta = m\,c_v(\vartheta_3 - \vartheta_2) \end{aligned}$$

The increased thermal energy $q_{2,3}$ is caused by combustion of the gas.

$3 \rightarrow 4$: Isentropic expansion, $dq = 0$:

$$\begin{aligned} q_{3,4} &= 0 \\ dw &= -du = -m\,c_v\,d\vartheta \\ w_{3,4} &= -\int_3^4 m\,c_v\,d\vartheta = -m\,c_v(\vartheta_4 - \vartheta_3) \end{aligned}$$

This state change describes the power stroke of the engine where $w_{3,4}$ is the output of kinetic energy from the gas, which is positive ($\vartheta_4 < \vartheta_3$).

$4 \rightarrow 1$: Isochoric heat loss, $dV = 0$:

$$
\begin{aligned}
dw &= p\, dV = 0 \\
w_{4,1} &= \int_4^1 p\, dV = 0 \\
dq &= du + dw = m\, c_v\, d\vartheta \\
q_{4,1} &= m\, c_v \int_4^1 d\vartheta = m\, c_v (\vartheta_1 - \vartheta_4)
\end{aligned}
$$

The loss of thermal energy $q_{4,1}$ is due to the gas exchange: The burnt hot gas is pumped into the exhaust and the combustion chamber is filled with a cold mixture of unburnt fuel vapour and air ($q_{4,1}$ is negative because of $\vartheta_1 < \vartheta_4$).

$$
\begin{aligned}
\eta_{th} &= \frac{w_{1,2} + w_{2,3} + w_{3,4} + w_{4,1}}{q_{2,3}} \\
&= \frac{m\,c_v(-\vartheta_2 + \vartheta_1 - \vartheta_4 + \vartheta_3)}{m\,c_v(\vartheta_3 - \vartheta_2)} \\
&= 1 - \frac{\vartheta_4 - \vartheta_1}{\vartheta_3 - \vartheta_2} \\
&= 1 - \frac{\vartheta_1}{\vartheta_2}\,\frac{\vartheta_4/\vartheta_1 - 1}{\vartheta_3/\vartheta_2 - 1}
\end{aligned}
$$

- **K = Cp/CV**

$$\frac{\vartheta_4}{\vartheta_3} = \left(\frac{V_3}{V_4}\right)^{\kappa-1} = \frac{1}{\varepsilon^{\kappa-1}} = \frac{\vartheta_1}{\vartheta_2}$$

$$\eta_{th} = 1 - \frac{1}{\varepsilon^{\kappa-1}}$$

Please note that the thermal efficiency η_{th} does not depend on the absolute temperature values. It mainly depends on the compression ratio ϵ. Example: For a compression ratio of $\varepsilon = 11$ and an adiabatic coefficient of $\kappa = 1.4$ the theoretical thermal efficiency η_{th} is:

$$\eta_{th} = 0.617$$

$$w_i = \frac{1}{V_d} \sum_{j=1}^{CYL} \oint \Big(p_j(V_j) - p_0 \Big) dV_j \quad , \qquad ($$

where:

$V_d = CYL \cdot (V_1 - V_2)$	is the displacement volume of all cylinders
CYL	is the number of cylinders
w_i	is the (normalised) indicated specific work.

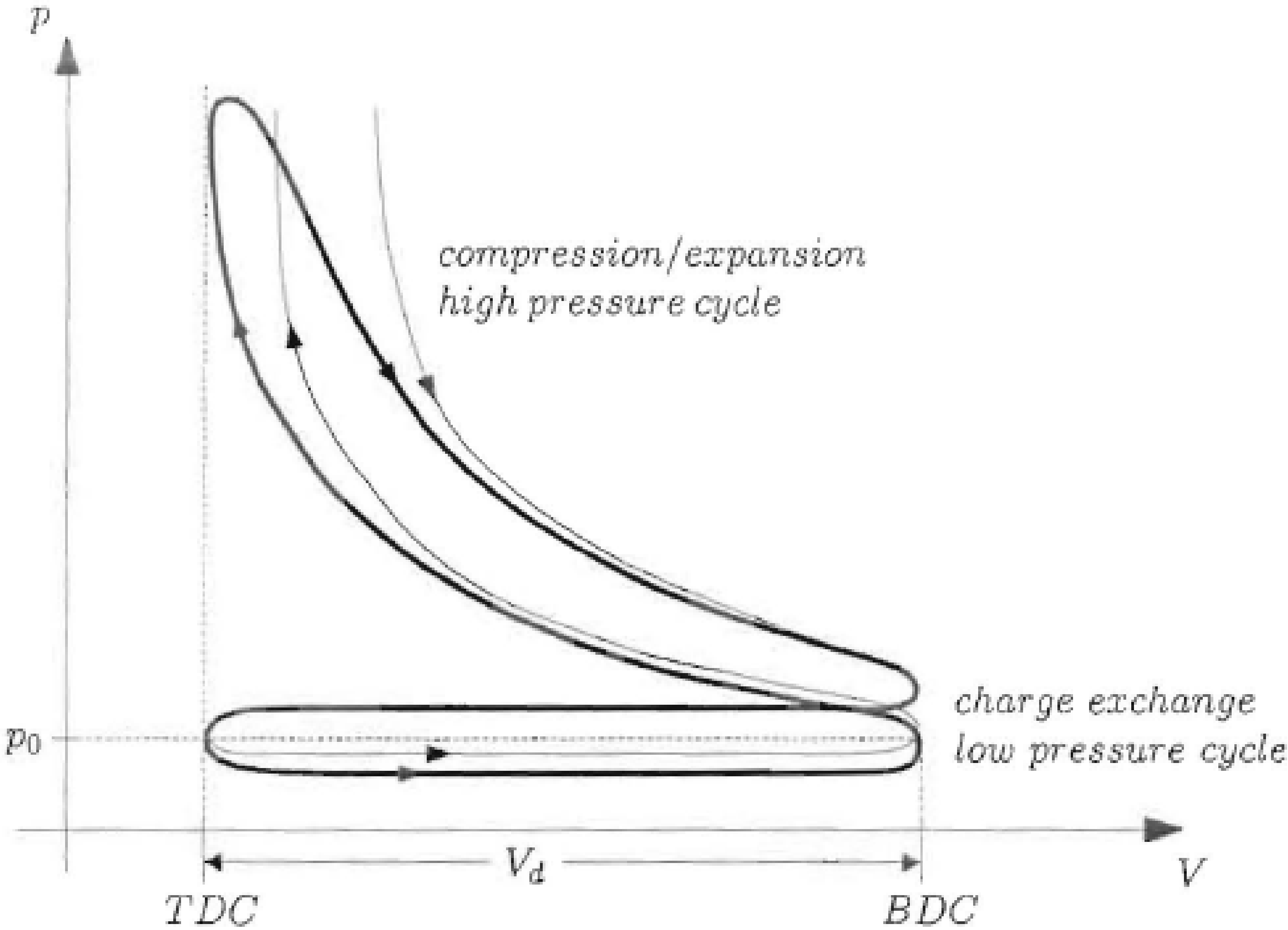


Figure 3.1 pV-diagram of four-stroke combustion engine

The piston stroke from Top Dead Center (TDC) is

$$s(\alpha_{CS}) = l(1 - \cos\beta) + r(1 - cos\alpha_{CS}) \quad .$$

From Figure 3.2 we get

$$\begin{aligned} l \sin\beta &= r \sin\alpha_{CS} \quad , \\ \cos\beta &= \sqrt{1 - \frac{r^2}{l^2} \sin^2\alpha_{CS}} \quad , \end{aligned} \tag{3.2}$$

which yields the piston stroke as

$$s(\alpha_{CS}) = r\left(1 - cos\alpha_{CS} + \frac{l}{r}\left(1 - \sqrt{1 - \frac{r^2}{l^2}\sin^2\alpha_{CS}}\right)\right) \quad . \tag{3.3}$$

At Top Dead Center, we have $\alpha_{CS} = 0$, $s(\alpha_{CS}) = 0$, and at Bottom Dead Center

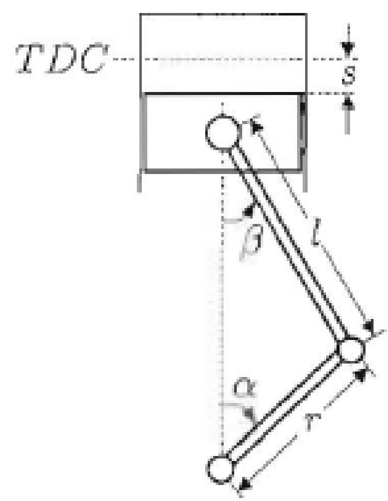


Figure 3.2 Piston and crankshaft motion

$\alpha_{CS} = \pi$, $s(\alpha_{CS}) = 2r$ respectively. The derivatives of the piston stroke are

$$\frac{ds}{d\alpha_{CS}} = r\left(\sin\alpha_{CS} + \frac{r}{l}\cdot\frac{\sin\alpha_{CS}\cos\alpha_{CS}}{\sqrt{1-\frac{r^2}{l^2}\sin^2\alpha_{CS}}}\right)$$

and

$$\frac{d^2s}{d\alpha_{CS}^2} = r\left(\cos\alpha_{CS} + \frac{\frac{r}{l}(\cos^2\alpha_{CS}-\sin^2\alpha_{CS}) + \frac{r^2}{l^2}\sin^4\alpha_{CS}}{\left(\sqrt{1-\frac{r^2}{l^2}\sin^2\alpha_{CS}}\right)^3}\right) \quad . (3.4)$$

These derivatives over crankshaft angle can be related to the derivatives over time as follows:

$$\begin{aligned}
\dot{s} &= \frac{ds}{dt} = \frac{ds}{d\alpha_{CS}} \cdot \frac{d\alpha_{CS}}{dt} = \frac{ds}{d\alpha_{CS}} \cdot \dot{\alpha}_{CS} \\
\ddot{s} &= \frac{d^2 s}{dt^2} = \frac{d}{dt}\left(\frac{ds}{d\alpha_{CS}} \cdot \frac{d\alpha_{CS}}{dt}\right) = \frac{d}{dt}\left(\frac{ds}{d\alpha_{CS}}\right) \cdot \frac{d\alpha_{CS}}{dt} + \frac{ds}{d\alpha_{CS}} \cdot \frac{d^2\alpha_{CS}}{dt^2} \\
&= \frac{d^2 s}{d\alpha_{CS}^2} \cdot \dot{\alpha}_{CS}^2 + \frac{ds}{d\alpha_{CS}} \cdot \ddot{\alpha}_{CS} \qquad (3.5)
\end{aligned}$$

The indicated specific work can be written as

$$\begin{aligned}
w_i &= \frac{1}{V_d} \oint \sum_{j=1}^{CYL} \left(p_j(\alpha_{CS}) - p_0\right) A_p \frac{ds_j(\alpha_{CS})}{d\alpha_{CS}} d\alpha_{CS} \\
&= \frac{1}{V_d} \oint T_{comb}(\alpha_{CS}) d\alpha_{CS} \quad . \qquad (3.6)
\end{aligned}$$

The combustion torque at the crankshaft is thus defined as

$$T_{comb}(\alpha_{CS}) = \sum_{j=1}^{CYL} \left(p_j(\alpha_{CS}) - p_0\right) A_p \frac{ds_j}{d\alpha_{CS}} \quad . \qquad (3.7)$$

The piston strokes in different cylinders are shifted by phase.

$$s_j(\alpha_{CS}) = s\left(\alpha_{CS} - (j-1)\cdot\frac{4\pi}{CYL}\right) \quad , \quad j = 1, ..., CYL \tag{3.8}$$

The average combustion torque is

$$\begin{aligned}\bar{T}_{comb} &= \frac{1}{4\pi}\oint T_{comb}(\alpha_{CS})d\alpha_{CS} \\ &= \frac{P_i}{\dot{\alpha}_{CS}} \quad ,\end{aligned} \tag{3.9}$$

where P_i is the mean indicated power. The total indicated work $w_i V_d$ can now be written at stationary engine operation as

$$w_i V_d = 4\pi\bar{T}_{comb} = 4\pi\frac{P_i}{\dot{\alpha}_{CS}} = \frac{4\pi P_i}{2\pi n} = \frac{2P_i}{n} \quad ,$$

and the normalised work

$$w_i = \frac{2P_i}{V_d\, n} \quad , \tag{3.10}$$

$$\eta_e = \frac{P_e}{m_f\,H_f} = \frac{w_e\,V_d\,n}{2m_f\,n\,H_f} \cdot \frac{2}{CYL} = \frac{w_e}{m_f\,H_f} \cdot \frac{V_d}{CYL} \quad .$$

P_e	is the effective power in W
w_e	is the effective specific work per cycle in J/m^3
m_f	is the mass of fuel measured per cylinder in kg
$\dot{m}_f$	is the fuel flow in kg/s
H_f	is the specific energy of the fuel released in the combustion J/kg
V_d	is the total displacement volume in m^3 (V_d/CYL displacement volume per cylinder)

The indicated thermodynamic efficiency (friction not considered) is:

$$\eta_i = \frac{w_i}{2m_f H_f} \cdot \frac{V_d}{CYL} \tag{3.12}$$

Table 3.1 Indicated specific work w_i, theoretical heat loss $q_{hl,th}$, and realistic heat loss $q_{hl,r}$ for different engine types, related to fuel combustion heat.

Engine Type	SI	Diesel	Big Diesel
w_i	33-35 %	40-43 %	45-48 %
$q_{hl,th}$	23-28 %	22-25 %	12-14 %
$q_{hl,r}$	37-44 %	35-40 %	26-33 %

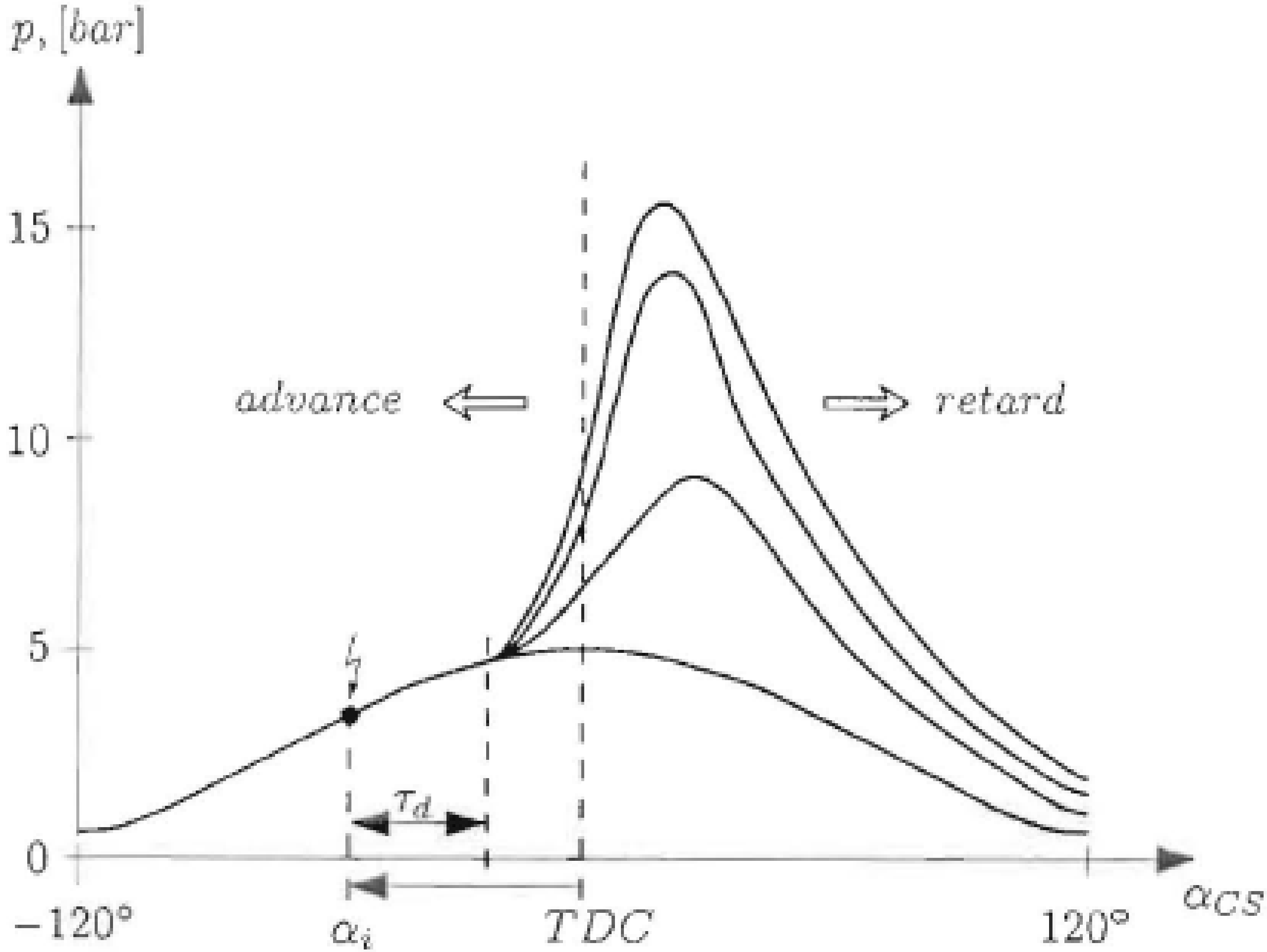


Figure 3.9 In-cylinder pressure p over crankshaft angle α_{CS}.

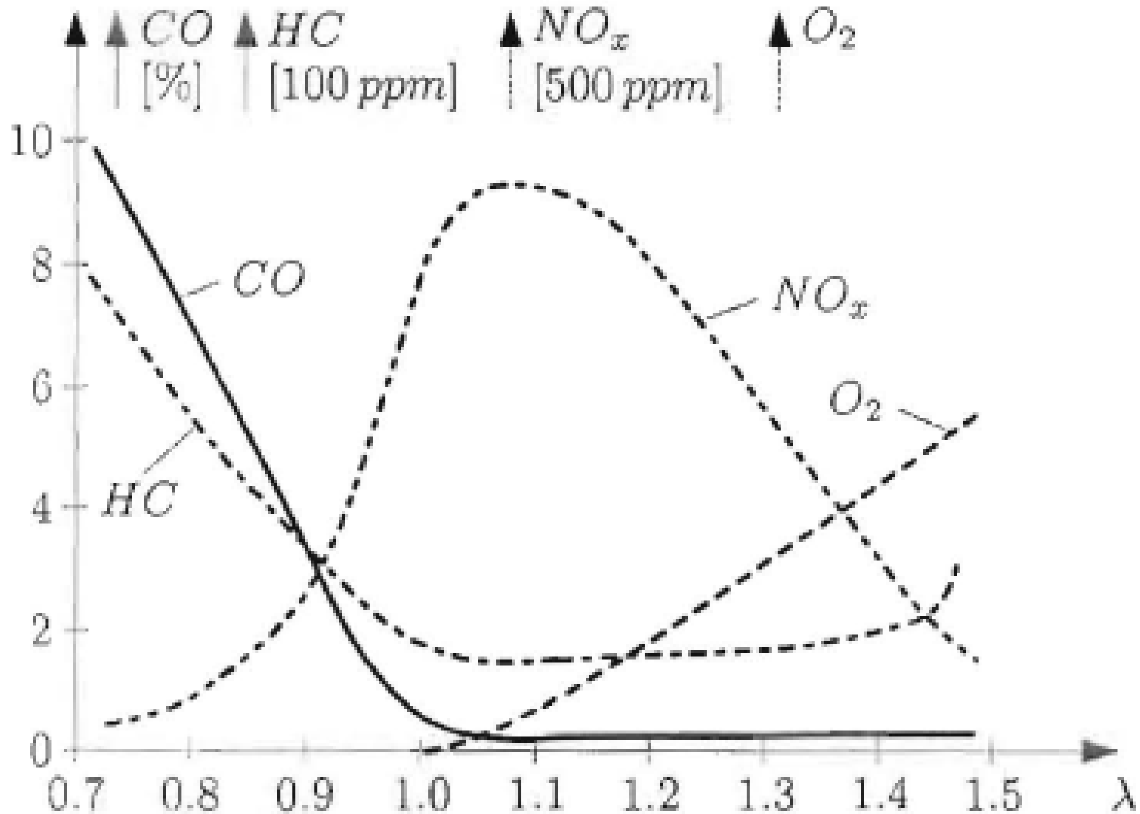


Figure 3.14 Raw emissions of CO, HC, NO_x and O_2 over air-fuel ratio λ for SI engines.

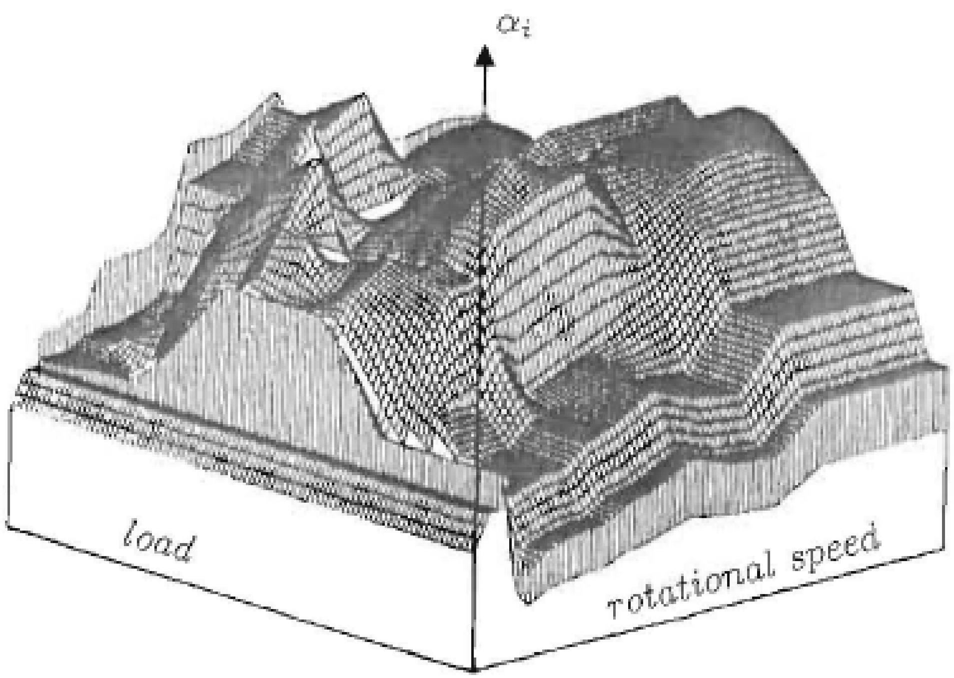


Figure 3.21 Ignition angle map

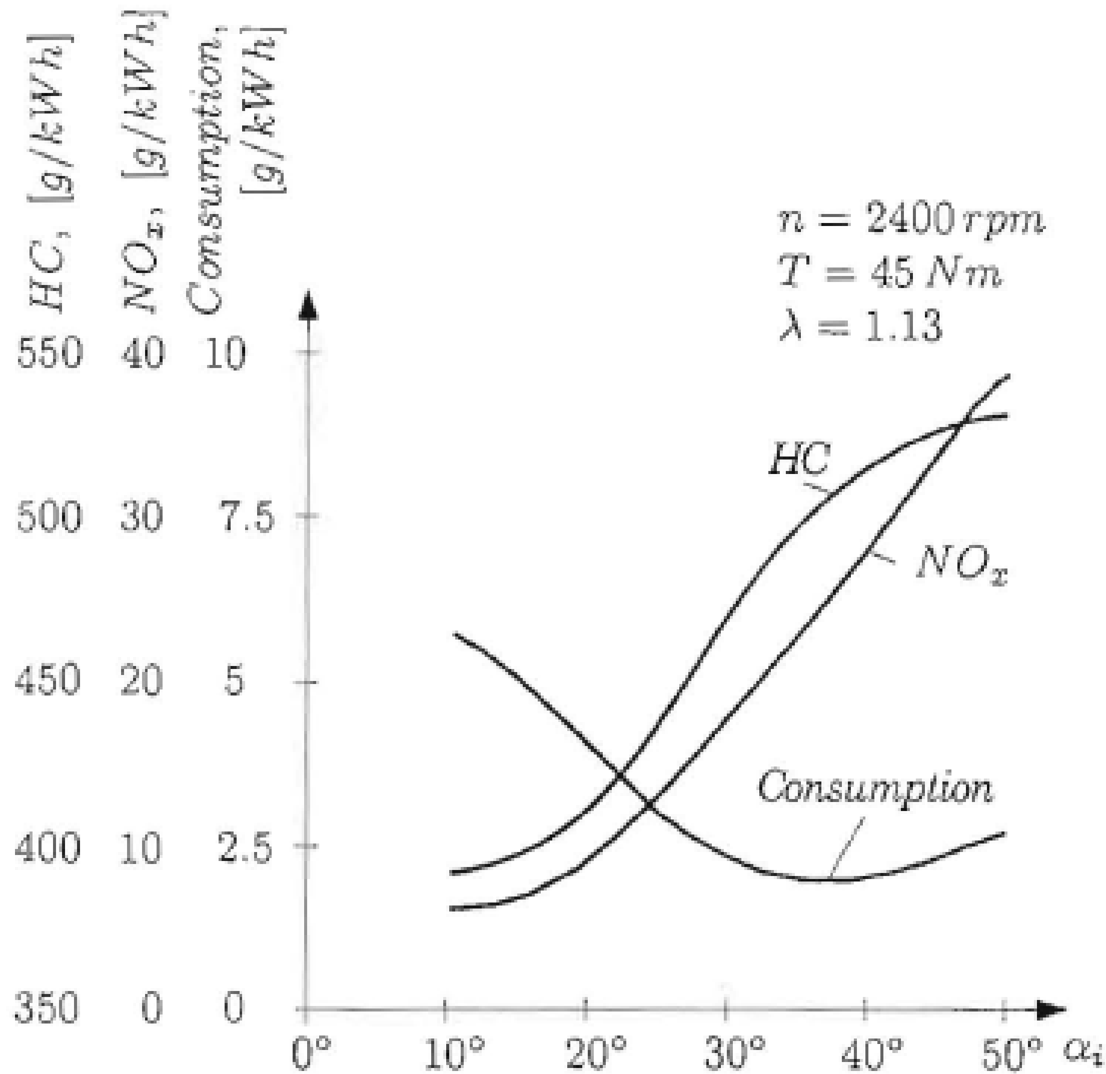
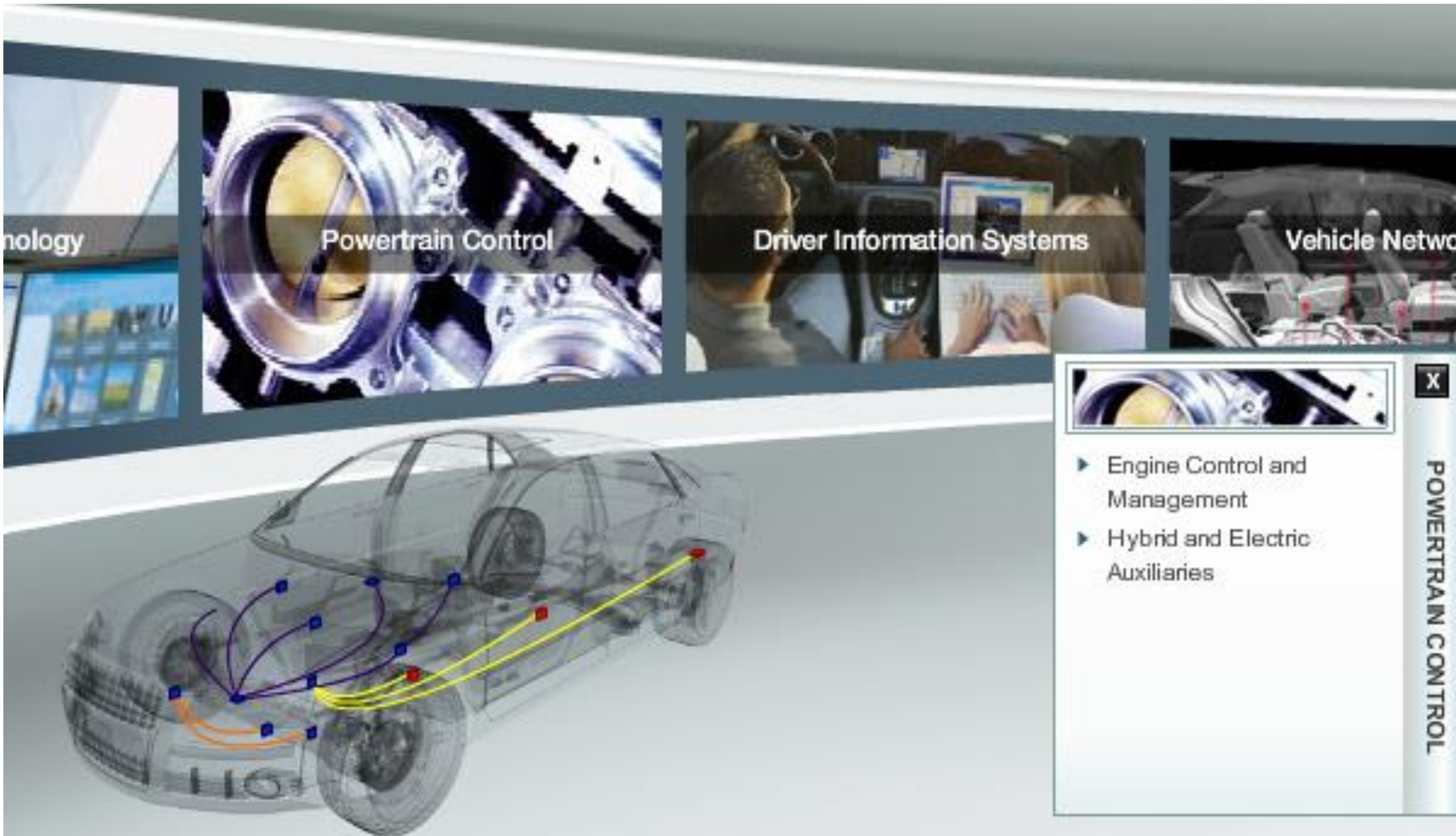
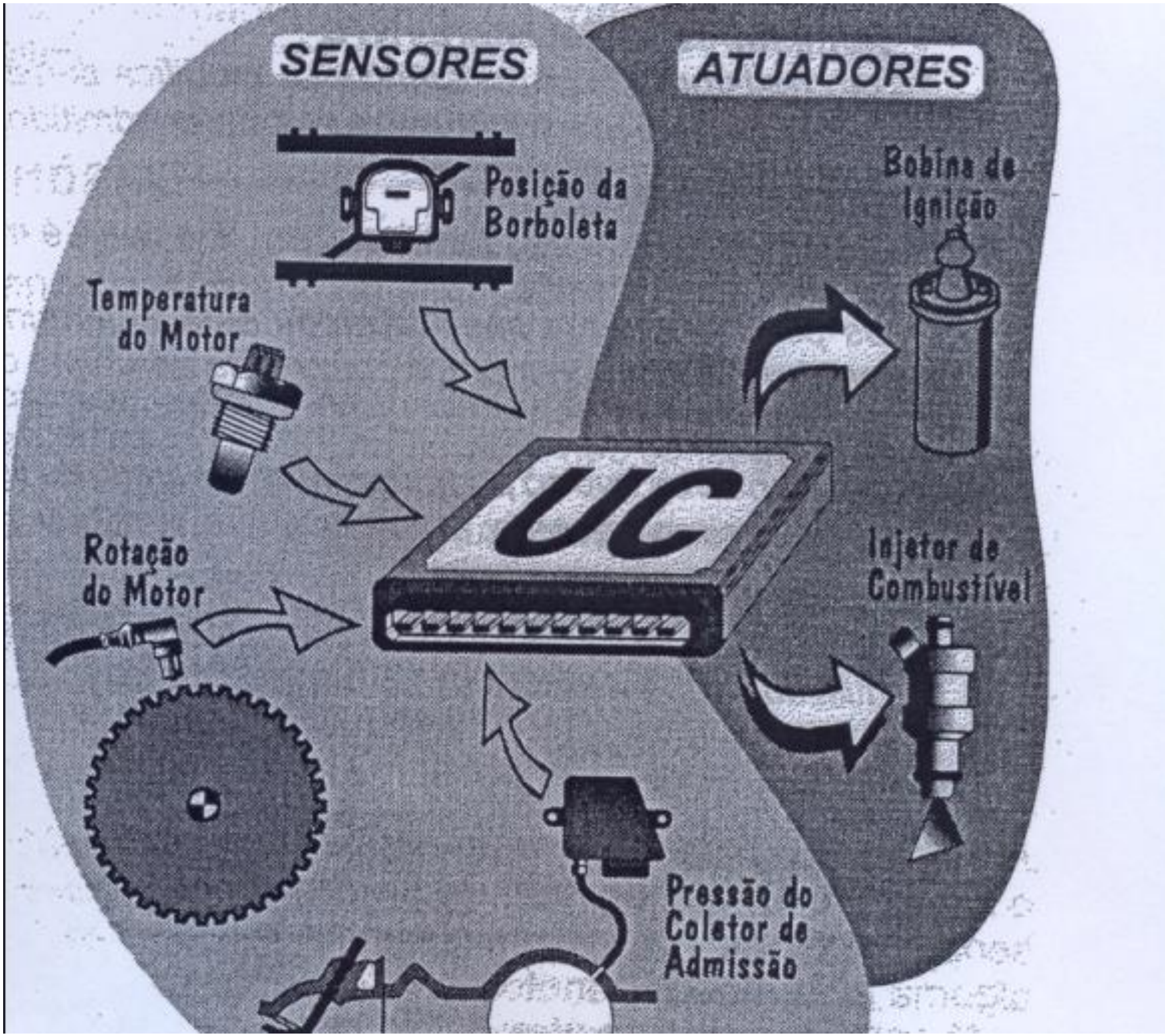
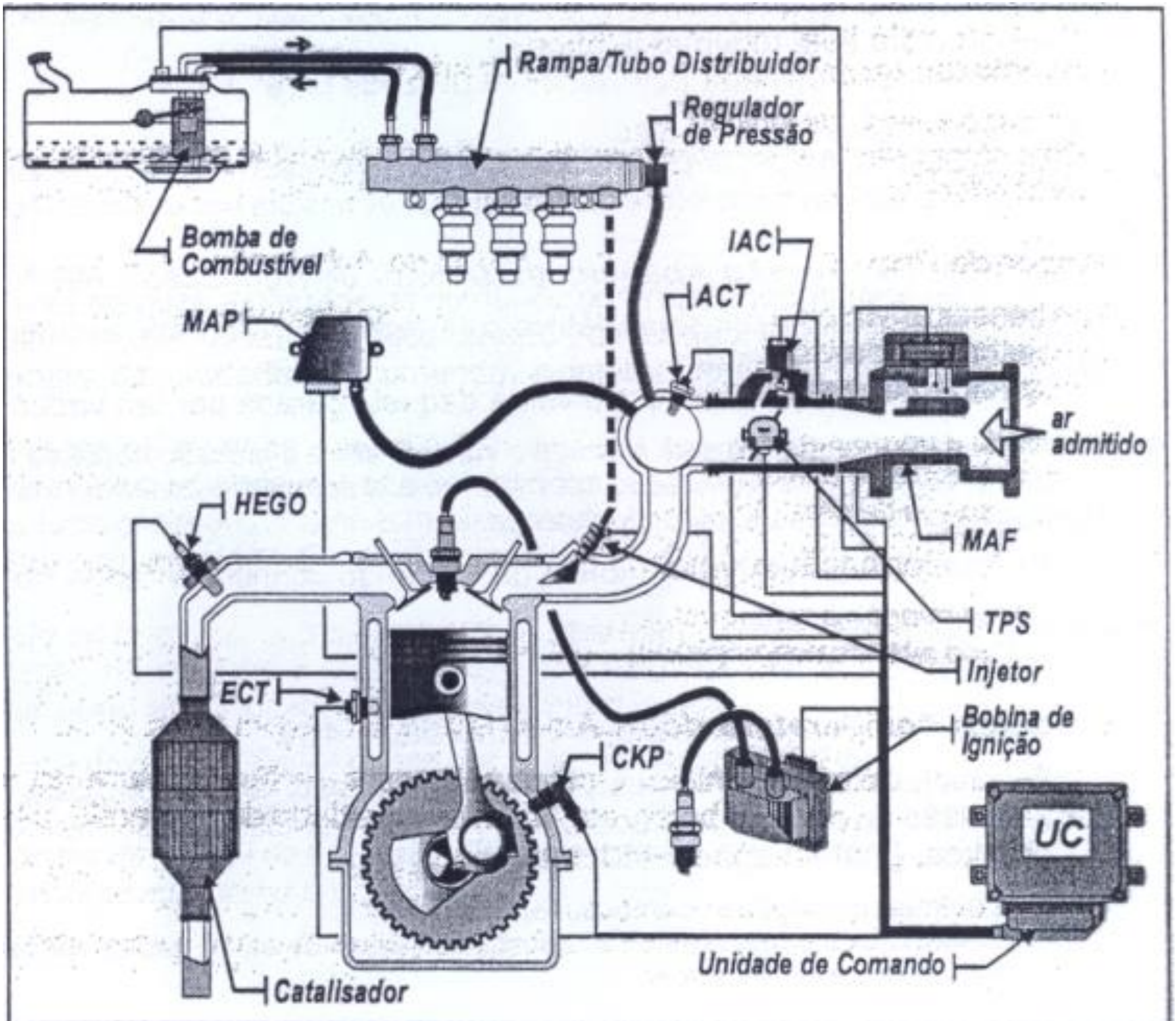


Figure 3.22 Fuel consumption and emission levels over ignition angle α_i.

GERENCIAMENTO DO MOTOR




SENSORES
ATUADORES
Posição da Borboleta
Temperatura do Motor
Rotação do Motor
Pressão do Coletor de Admissão
UC
Bobina de Ignição
Injetor de Combustível



Rampa/Tubo Distribuidor
Regulador de Pressão
Bomba de Combustível
IAC
ACT
MAP
ar admitido
HEGO
MAF
TPS
Injetor
ECT
Bobina de Ignição
CKP
UC
Unidade de Comando
Catalisador