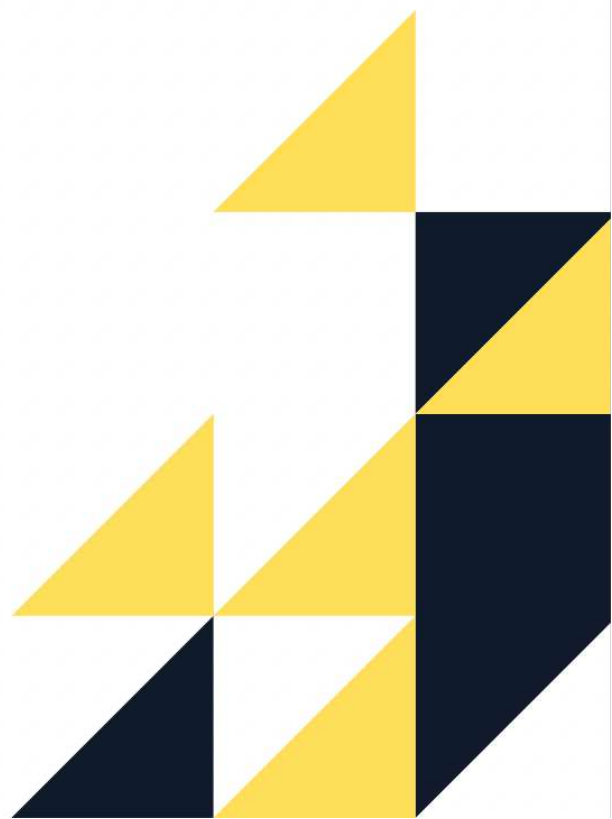


FORMULARIO



SISTEMA INTERNAZIONALE DELLE UNITÀ DI MISURA

Grandezza fisica	Simbolo della grandezza	Nome dell'unità di misura	Simbolo dell'unità di misura
lunghezza	l	metro	m
massa	m	kilogrammo	kg
tempo	t	secondo	s
corrente elettrica	I	ampere	A
temperatura	T	kelvin	K
quantità di sostanza	n	mole	mol
intensità luminosa	i _v	candela	cd

• $\Delta^{\circ}\text{C} = \Delta\text{K}$

$4,186 \frac{\text{kJ}}{\text{kg}^{\circ}\text{C}} = 4,186 \frac{\text{kJ}}{\text{kg}\text{K}}$ perché $\Delta U = mc\Delta T$

LOGARITMI

$$\ln A \pm \ln B = C \quad \Rightarrow \quad \begin{cases} (+) \ln(A \cdot B) = C \\ (-) \ln \frac{A}{B} = C \end{cases} \quad \Rightarrow \quad \begin{cases} AB = e^C \\ \frac{A}{B} = e^C \end{cases}$$

RADICI

$\sqrt[n]{A} = A^{1/n}$

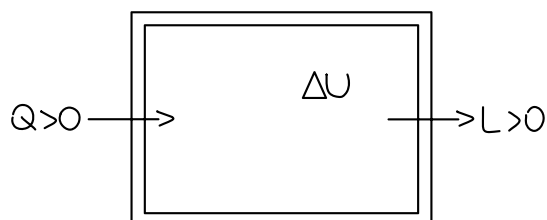
POTENZE

$A^n = B \quad \Rightarrow \quad \sqrt[n]{A^n} = \sqrt[n]{B} \quad \Rightarrow \quad A^{n/n} = B^{1/n} \quad \Rightarrow \quad A = B^{1/n}$

SISTEMI CHIUSI \rightarrow bilanci energetici

• SOSTANZE IDEALI $\begin{cases} \text{gas ideali} \\ \text{solidi e liquidi ideali} \end{cases} \Rightarrow$ incompressibili

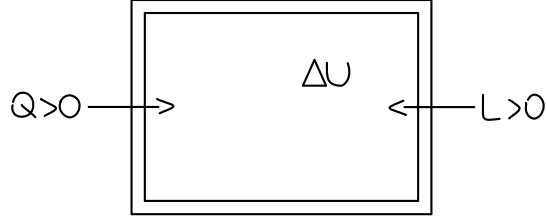
I CONVENZIONE: $\Delta U = Q - L$



CALORE
+ : entra
- : esce

LAVORO
+ : esce
- : entra

II CONVENZIONE: $\Delta U = Q - L$



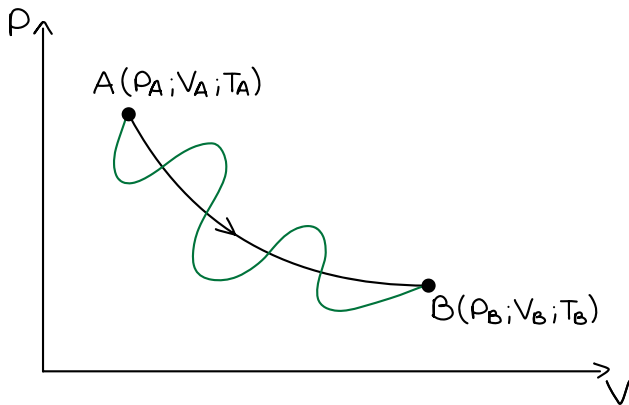
CALORE
 + : entra
 - : esce

LAVORO
 + : entra
 - : esce

• **FUNZIONI DI STATO**: il valore della grandezza dipende soltanto dallo stato termodinamico in cui si è

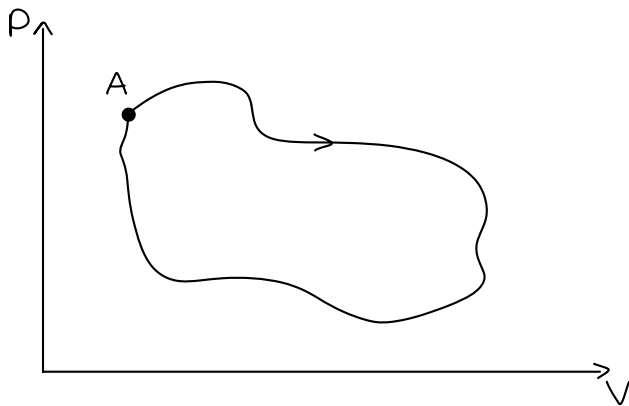
- Energia interna (U)
- Entalpia (H)
- Entropia (S)

$$\begin{cases} dU = \delta Q - \delta L \end{cases}$$



$$\Delta U = U_B - U_A$$

N.B. La variazione di energia interna non dipende dal percorso, ma dal punto iniziale e finale.



$$\begin{aligned} \Delta U &= 0 \\ \Delta H &= 0 \\ \Delta S &= 0 \end{aligned}$$

$$\Delta U = m \cdot c_v \cdot \Delta T$$

calore specifico a volume costante

N.B. vale per ogni trasformazione (anche se V non è costante)
 se V = costante $\Rightarrow \Delta U = Q$, L = 0

$$\Delta H = m \cdot c_p \cdot \Delta T$$

calore specifico a pressione costante

N.B. vale per ogni trasformazione (anche se P non è costante)
 se P = costante $\Rightarrow \Delta H = Q$

$$\begin{cases} \Delta U = Q - L \\ \Delta U = m \cdot c_v \cdot \Delta T \\ \Delta H = m \cdot c_p \cdot \Delta T \end{cases} \Rightarrow L = m(c_p - c_v)\Delta T$$

• **GAS IDEALI**

- EQUAZIONE DI STATO: $PV = nR_u T$

$$R_u = 8,31447 \frac{\text{J}}{\text{mol} \cdot \text{K}}$$

conoscendo la massa $PV = MM \cdot n \frac{R_u}{MM} \cdot T = mRT$

$$P \frac{V}{m} = RT$$

$$Pv = RT$$

- TRASFORMAZIONE ISOCORA

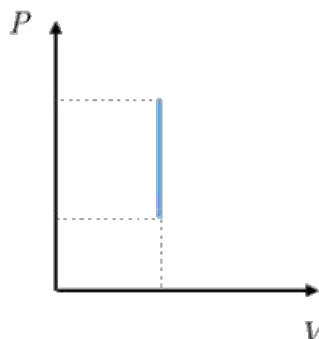
$V = \text{costante}$

$$PV = nR_u T \Rightarrow \frac{P}{T} = \frac{nR_u}{V} = \text{costante}$$

$$L = \int_A^B P dV = 0$$

$$\Delta U = Q - L = mc_v \Delta T = n \tilde{c}_v \Delta T$$

calore specifico
per unità di moli



GAS	\tilde{c}_v	\tilde{c}_p	$k = \frac{\tilde{c}_p}{\tilde{c}_v}$
MONOATOMICO	$\frac{3}{2} R_u$	$\frac{5}{2} R_u$	$\frac{5}{3}$
BIATOMICO	$\frac{5}{2} R_u$	$\frac{7}{2} R_u$	$\frac{7}{5}$
POLIATOMICO	$\frac{7}{2} R_u$	$\frac{9}{2} R_u$	$\frac{9}{7}$

$$\tilde{c}_v + R_u = \tilde{c}_p$$

$$c_v + R = c_p$$

- TRASFORMAZIONE ISOBARA

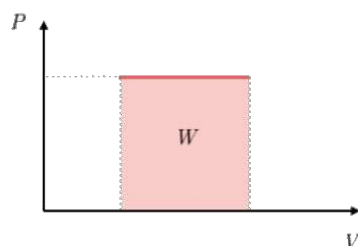
$P = \text{costante}$

$$PV = nR_u T \Rightarrow \frac{V}{T} = \frac{nR_u}{P} = \text{costante}$$

$$L = \int_A^B P dV = P \int_A^B dV = P \Delta V = nR_u \Delta T$$

$$\Delta U = mc_v \Delta T$$

$$\Delta U = Q - L \Rightarrow Q = \Delta U + L = mc_v \Delta T + mR \Delta T = m(\underbrace{c_v + R}_{\text{Mayer}}) \Delta T = m c_p \Delta T = \Delta H$$



- TRASFORMAZIONE ISOTERMA

$T = \text{costante}$

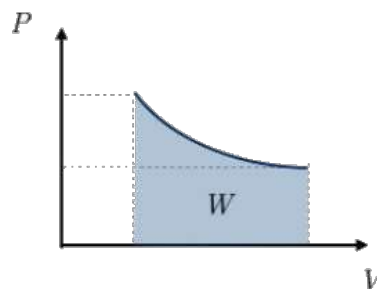
$$PV = nR_u T = \text{costante}$$

$$\Delta U = Q - L = mc_v \Delta T = 0 \Rightarrow Q = L$$

$$L = \int_A^B P dV = nR_u T \int_A^B \frac{1}{V} dV = nR_u T \ln \frac{V_B}{V_A} = nR_u T \ln \frac{P_A}{P_B}$$

$$= P_A V_A \ln \frac{P_A}{P_B} = P_B V_B \ln \frac{P_A}{P_B}$$

$$\Delta H = m c_p \Delta T = 0$$

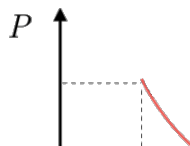


- TRASFORMAZIONE ADIABATICA

$Q = \text{costante}$

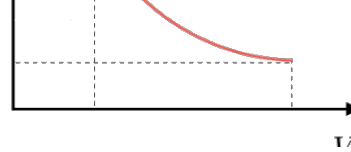
$$PV^k = \text{costante}$$

$$k = \frac{c_p}{c_v}$$



$$\Delta U = Q - L = mc_v \Delta T$$

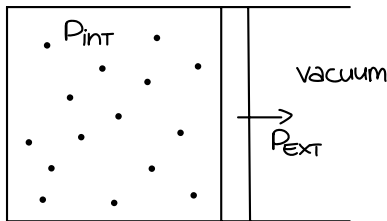
$$\Delta H = mc_p \Delta T$$



SOLIDI E LIQUIDI IDEALI (INCOMPRESSIBILI)

$$\Delta U = mc \Delta T \begin{cases} \text{solidi} \rightarrow \Delta H = \Delta U \\ \text{liquidi} \rightarrow \Delta H = \Delta U + V \Delta P \end{cases}$$

- Lasciamo libero il gas di espandersi



$$L = 0 \quad \text{perché } F_{\text{EST}} = 0$$

VARIAZIONE DI ENTROPIA (GAS IDEALE)

$$\Delta S = m(s_2 - s_1)$$

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

$$\Delta S_{\text{IRR}} = \Delta S_{\text{REV}}$$

$$\Delta S_{\text{TOT}} = \Delta S_{\text{AMBIENTE}} + \Delta S_{\text{SISTEMA}}$$

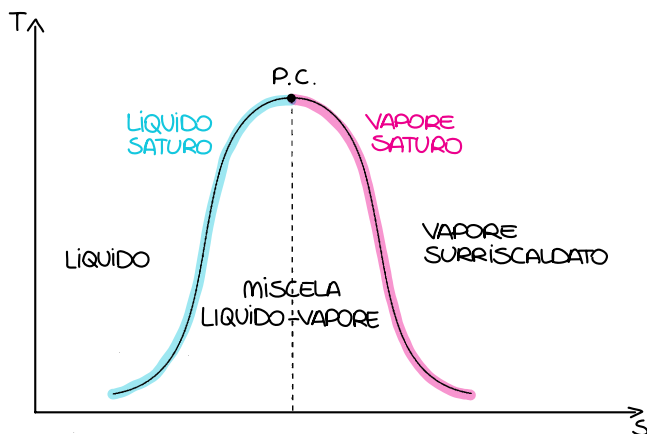
RISERVA DI TEMPERATURA

$$\Delta S_{\text{RT}} = \frac{Q}{T_{\text{RT}}} \quad Q > 0 \text{ se entrante nella riserva}$$

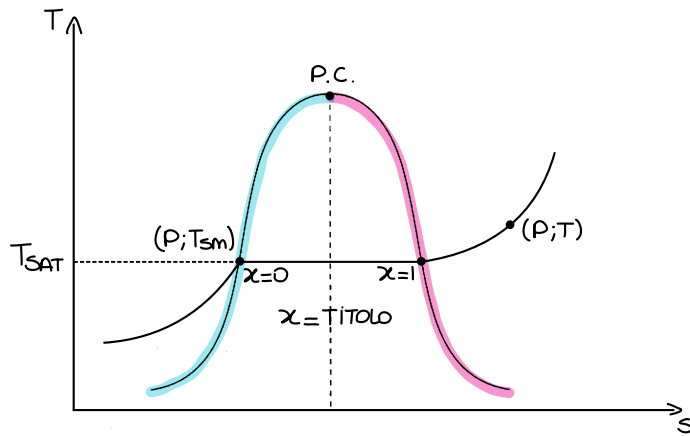
LIQUIDI E SOLIDI (INCOMPRESSIBILI)

$$c_p = c_v = c$$

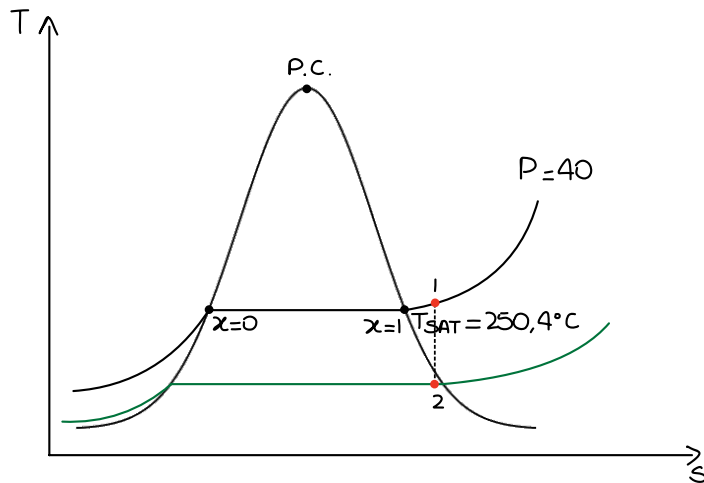
$$s_2 - s_1 = c \ln \frac{T_2}{T_1} \Rightarrow \Delta S = 0 \Rightarrow T_2 \approx T_1$$



TRASFORMAZIONE ISOBARA ($P = \text{costante}$)

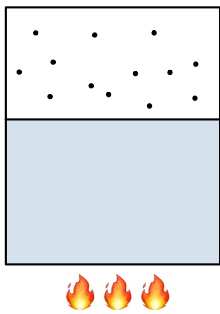


$$x = \frac{s_2 - s_{1s}}{s_{vs} - s_{1s}} = \frac{h_2 - h_{1s}}{h_{vs} - h_{1s}}$$



$$h_2 = h_{1s} + x(h_{vs} - h_{1s})$$

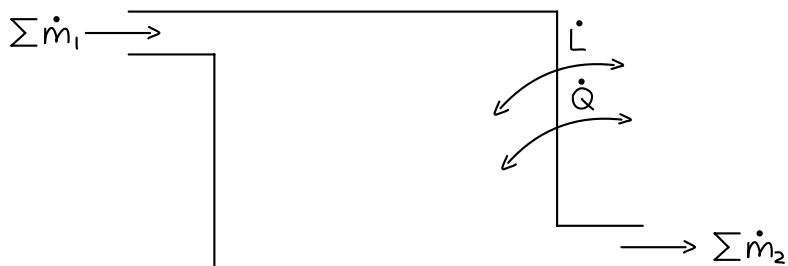
OSSERVAZIONE: PENTOLA A PRESSIONE



$$V = \text{costante}$$

$$v = \frac{V}{m} = \text{costante}$$

SISTEMI APERTI



$$\int \frac{dM}{dt} = \dot{m}_1 - \dot{m}_2 = 0$$

BILANCIO DI MASSA

$$\begin{cases} \frac{dE}{dt} = \dot{m}_1 h_1 - \dot{m}_2 h_2 + \dot{Q} - \dot{L} = 0 \\ \frac{dS}{dt} = \dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{S}_q + \dot{S}_{gen} = 0 \end{cases}$$

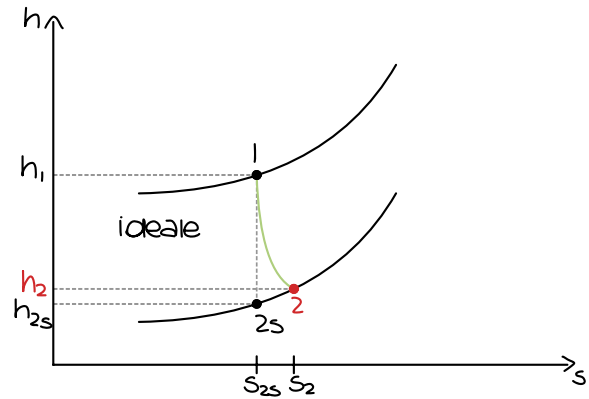
BILANCIO DI ENERGIA

BILANCIO DI ENTROPIA

• RENDIMENTO ISOENTROPICO (TURBINA)

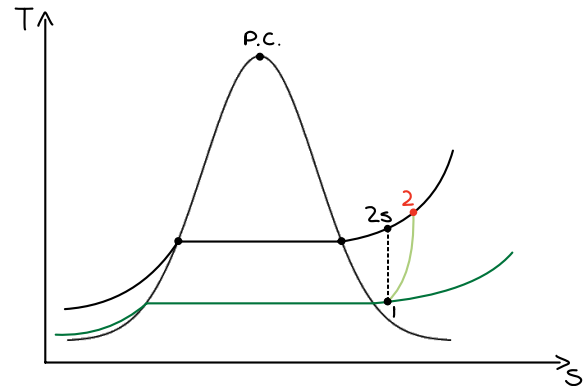
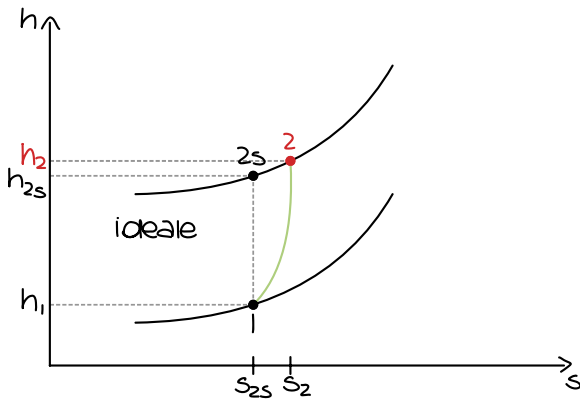
$$\eta_T = \frac{\dot{L}}{\dot{L}_{\max}} = \frac{\dot{L}}{\dot{L}_{\text{REV}}}$$

- 1- Calcolare T_{2s} dall'equazione di bilancio del caso ideale (isoentropico)
- 2- Nota T_{2s} , calcolare \dot{L}_{REV}
- 3- Noto η_T , ricavare \dot{L}
- 4- Da \dot{L} calcolare T_2 reale



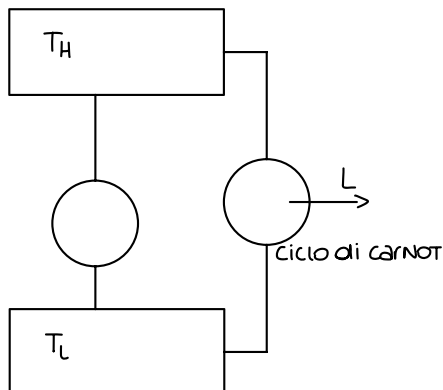
• RENDIMENTO ISOENTROPICO (COMPRESSORE)

$$\eta_c = \frac{\dot{L}_{\text{REV}}}{\dot{L}} < 1$$



$$\dot{L}_{\text{REV}} = \dot{m}(h_{2s} - h_1)$$

- **ENUNCIATO DI KELVIN-PLANCK**: È impossibile una trasformazione ciclica in cui l'unico risultato sia la trasformazione in lavoro di tutto il calore assorbito da una sorgente.



- **ENUNCIATO DI CLAUSIUS**: È impossibile realizzare una macchina ciclica, capace di trasformare calore da una sorgente a bassa temperatura ad una ad alta temperatura senza apporto di lavoro esterno.

N.B. È equivalente all'enunciato Kelvin-Planck

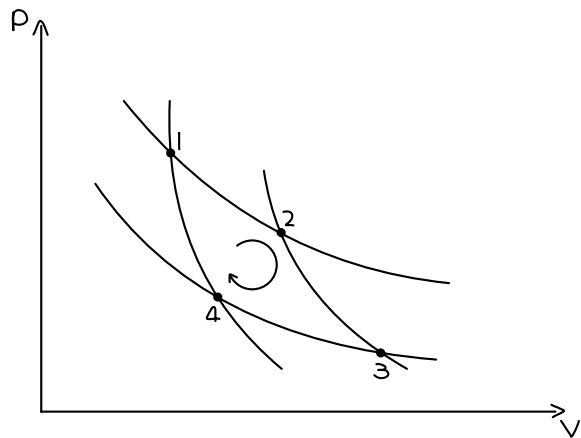
- RENDIMENTO DI UN CICLO TERMODINAMICO

$$\eta = 1 - \frac{|Q_L|}{|Q_H|}$$

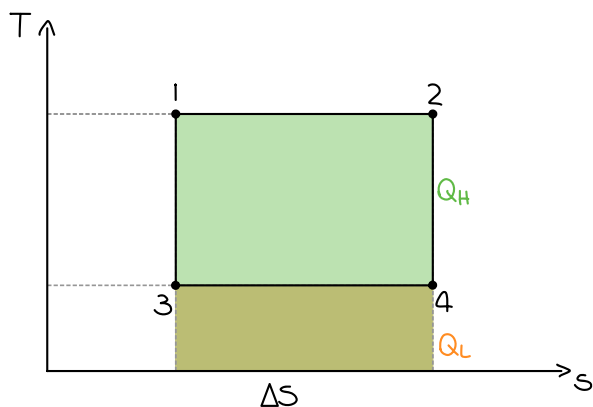
- CICLO DI CARNOT

$$\eta_{\text{CARNOT}} = 1 - \frac{T_L}{T_H} = \eta_{\text{MAX}}$$

$$\eta \begin{cases} < \eta_{\text{CARNOT}} & \text{CICLO IRREVERSIBILE} \\ = \eta_{\text{CARNOT}} & \text{CICLO REVERSIBILE} \\ > \eta_{\text{CARNOT}} & \text{CICLO IMPOSSIBILE} \end{cases}$$



1-2 : Espansione isoterma a T_H
 2-3 : Espansione adiabatrica reversibile
 3-4 : compressione isoterma a T_L
 4-1 : Compressione adiabatrica reversibile



$$\Delta U_{\text{CICLO}} = \Delta S_{\text{CICLO}} = \Delta H_{\text{CICLO}} = 0$$

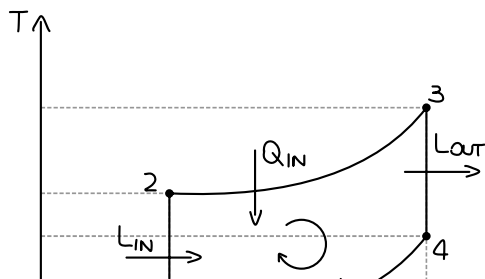
- RENDIMENTO DI II PRINCIPIO

$$\eta_{\text{II PRINCIPIO}} = \frac{\eta}{\eta_{\text{MAX}}}$$

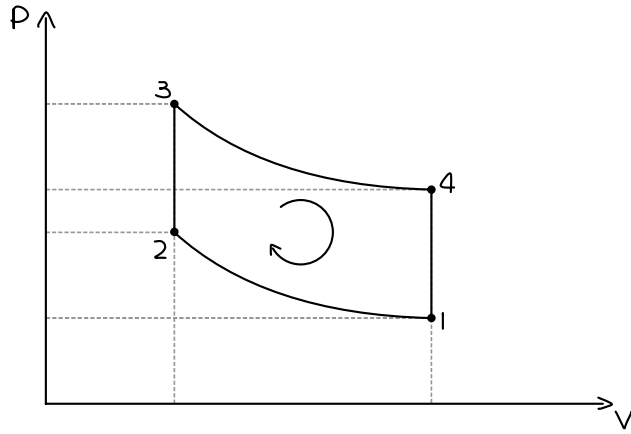
- MOTORE OTTO : motore a cilindri

- CILINDRATA V_C : somma dei volumi di ciascun cilindro

- CICLO OTTO IDEALE

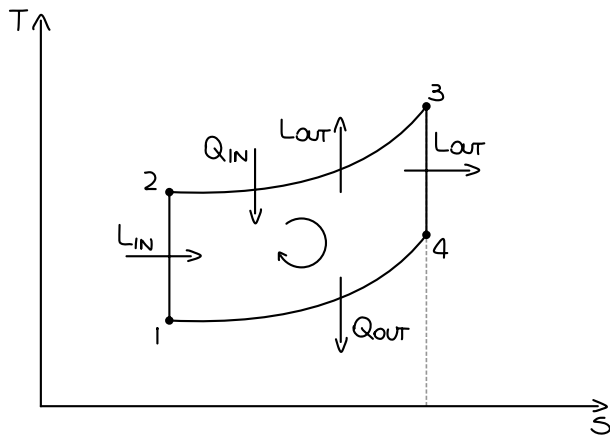


1-2 : Adiabatica
 2-3 : isocora
 3-4 : Adiabatica
 4-1 : isocora

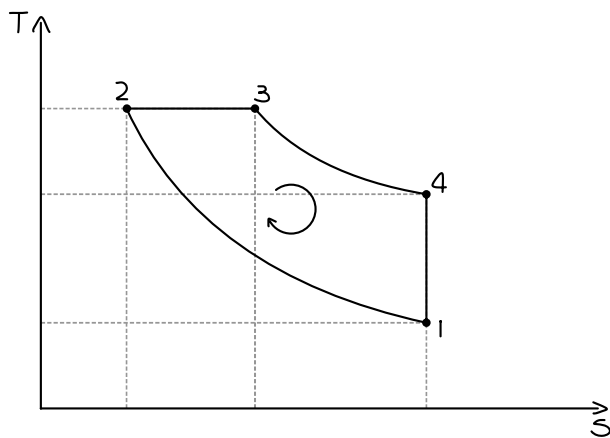


$$\beta = \frac{V_1}{V_2}$$

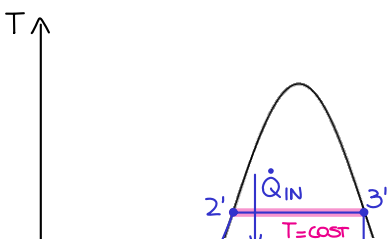
Ciclo DIESEL



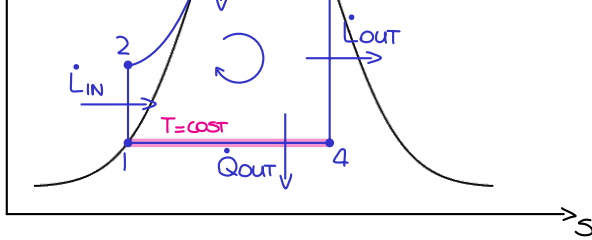
- 1-2 : Adiabatica
- 2-3 : isobara
- 3-4 : Adiabatica
- 4-1 : isocora



Ciclo RANKINE

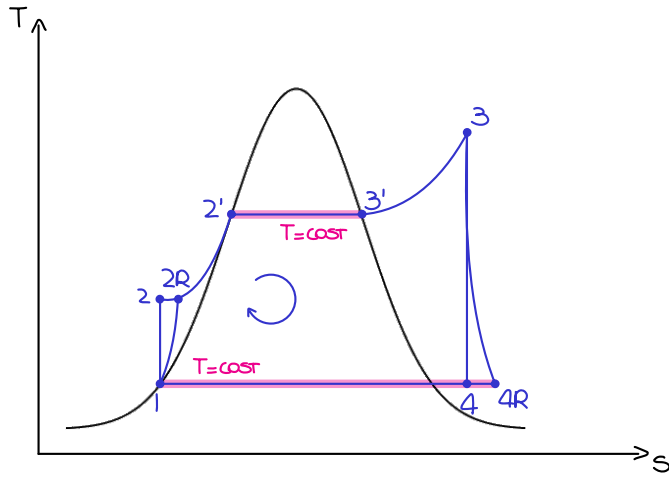


- 1-2 : pompa adiabatica (ideale)
- 2-3' : caldaia isobara (ideale)
- 3'-4 : Turbina adiabatica (ideale)



4-1: Scambiatore di calore (ideale)
 $P = \text{costante}$

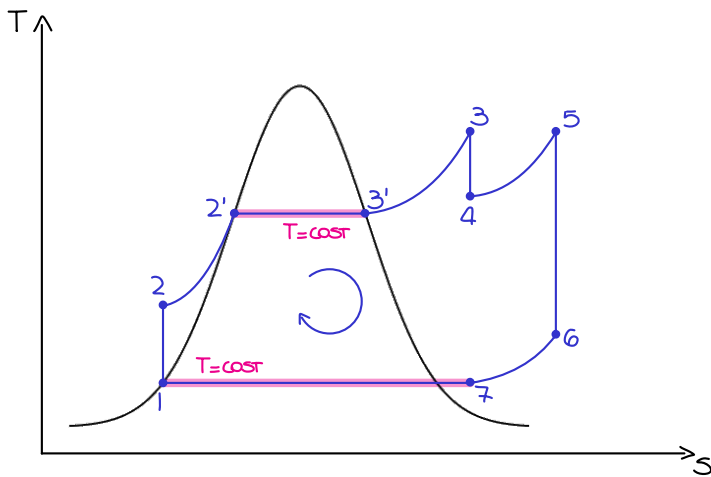
- CON SURRISCALDAMENTO



1-2: Pompa adiabatica (ideale)
 2-3: caldaia isobara (ideale)
 3-4: Turbina adiabatica (ideale)
 4-1: Scambiatore di calore (ideale)
 $P = \text{costante}$

N.B. Non si sa se il punto 4 sarà un punto di $\left\{ \begin{array}{l} \text{miscela liquido-vapore} \\ \text{vapore saturo} \\ \text{vapore surriscaldato} \end{array} \right.$

- CON RISURRISCALDAMENTO



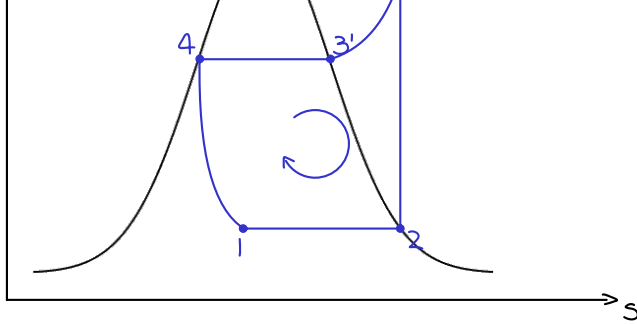
$$\dot{L}_{\text{UTILE}} = \dot{L}_{T,R} - |\dot{L}_{D,R}|$$

$$\eta = \frac{\dot{L}_{\text{UTILE}}}{\dot{Q}_H}$$

$$\dot{Q}_H = \dot{m} (h_3 - h_{2R})$$

$$\text{COP}_F = \frac{\dot{Q}_L}{\dot{L}} = \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L} = \frac{1}{\frac{\dot{Q}_H}{\dot{Q}_L} - 1} > 1$$





1-4: isoentropica
2-3: compressore

$$\text{COP}_F = \frac{q_L}{l} = \frac{|h_2 - h_1|}{|h_3 - h_2|}$$

$$|\dot{Q}_L| = \dot{m} q_L$$

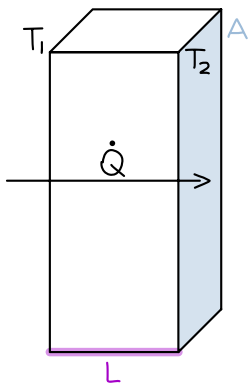
$$\dot{L}_C = \frac{|\dot{Q}_L|}{\text{COP}_F}$$

$$|\dot{Q}_S| = |\dot{L}_C| + |\dot{Q}_L|$$

$$\text{COP}_{PC} = \frac{\dot{Q}_H}{\dot{L}} = \frac{1}{1 - \frac{\dot{Q}_L}{\dot{Q}_H}} = 1 + \text{COP}_F$$

• INTERPOLAZIONE LINEARE: $T_3 = T_A + \Delta T \frac{s_3 - s_A}{s_B - s_A}$

• CONDUZIONE (solidi)

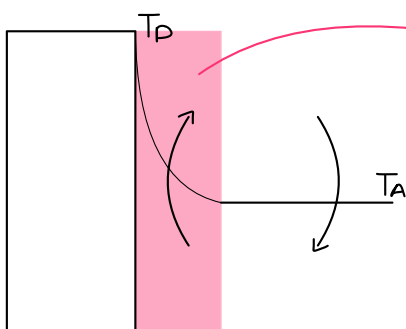


COEFFICIENTE DI CONDUZIONE TERMICA λ/k $\left[\frac{W}{m \cdot K} \right]$

$$\dot{Q} = \frac{\lambda \cdot A}{L} \Delta T = \frac{\Delta T}{R}$$

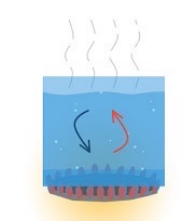


• CONVEZIONE (liquidi)



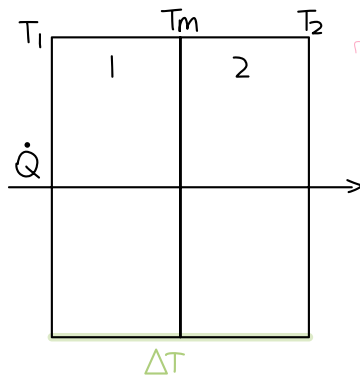
COEFFICIENTE DI CONVEZIONE TERMICA h $\left[\frac{W}{m^2 \cdot K} \right]$

$$\dot{Q} = h A \Delta T = \frac{\Delta T}{R}$$



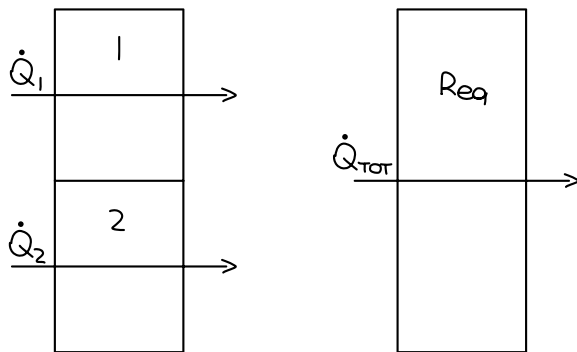
Non si sa cosa accade

- RESISTENZE IN SERIE: $R_{eq} = R_1 + R_2$



$$\begin{aligned}\dot{Q}_1 &= \dot{Q}_2 \\ \dot{Q} &= \frac{\Delta T_1}{R_1} \Rightarrow \Delta T_1 = \dot{Q} R_1 \\ \dot{Q} &= \frac{\Delta T_2}{R_2} \Rightarrow \Delta T_2 = \dot{Q} R_2 \\ \dot{Q} &= \frac{\Delta T}{R_{eq}} \Rightarrow \Delta T = \dot{Q} R_{eq} = \dot{Q} (R_1 + R_2)\end{aligned}$$

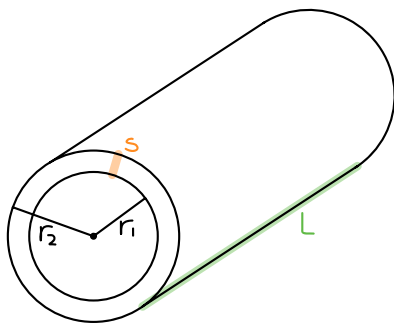
- RESISTENZE IN PARALLELO: $R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$



$$\begin{aligned}\dot{Q}_1 &= \frac{\Delta T}{R_1} \\ \dot{Q}_2 &= \frac{\Delta T}{R_2} \\ \dot{Q}_{tot} &= \frac{\Delta T}{R_{eq}}\end{aligned}$$

- RESISTENZA TOTALE $R_{tot} = \frac{l}{u \cdot A}$

- CILINDRO



$$\begin{aligned}S &= r_2 - r_1 \\ S &= \frac{d_2 - d_1}{2} \\ R &= \frac{\ln \frac{r_2}{r_1}}{2\pi L \lambda}\end{aligned}$$

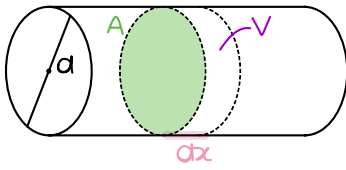
- SFERA

$$R = \frac{r_2 - r_1}{4\pi \lambda r_1 r_2}$$

- NUMERO DI REYNOLDS: $Re = \frac{\rho \cdot v \cdot \delta}{\mu}$
lunghezza caratteristica del problema
viscosità

- TUBO CILINDRICO: $\delta = d$
diametro interno

- PORTATA IN MASSA



$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot A \cdot \frac{dx}{dt}$$

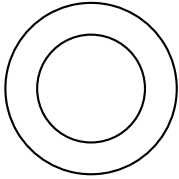
$$Re = \frac{\rho \cdot d \cdot \dot{V}}{\mu \cdot A} = \frac{\rho \cdot d \cdot \dot{V}}{\mu \cdot \frac{\pi d^2}{4}} = \frac{4\dot{m}}{\pi \mu d}$$

• DIAMETRO IDRAULICO:

$$D_H = \frac{4A}{P}$$

perimetro

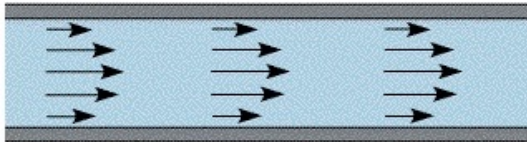
- SEZIONE ANULARE DI DUE TUBI CONCENTRICI



$$D_H = \frac{4\pi \frac{de^2 - di^2}{4}}{\pi (de + di)} = \frac{(de - di)(de + di)}{de + di} = de - di$$

• MOTO LAMINARE E TURBOLENTO

Laminar



$$Re < 2300$$

Turbulent



$$Re > 2300$$

• NUMERO DI PRANDTL:

$$Pr = \frac{c_p \cdot \mu}{k}$$

conduttività

N.B. Non dipende dalla geometria

• NUMERO DI NUSSELT:

$$Nu = \frac{h \cdot \delta}{k}$$