Centro Stampa

N° 1011

FONDAMENTI DI MACCHINE TEORIA ESECIZI
PROF. POGGIO DI MELLI ANTONIO

FONDAMENTI DI MACCHINE

RICHIAMI DI TERMODINAMICA

1 LEZIONE 29/09

Sistema termodinamico

per descrivere lo stato di un sistema ho bisogno dei parametri di stato:

- ESTERNI
  - Coord. spaz. e cinem.
- INTERNI
  - chimici (quando ho delle reazioni interne) non avrò però mai delle reazioni incomplete
  - fisici (T, P)
    - ↳ sforzi normali
    - ↳ sforzi tangenziali (lavoro d'attrito)

Hp: fluido continuo, isotropo, omogeneo.

LEGGI DI CONSERVAZIONE

- MASSA
- QUANTITÀ DI MOTO (e MOMENTO)
- ENERGIA ⟶ I principio termod. (conserv. energia)

↳ legge di evoluzione dell'energia ⟶ 2° principio termod. (entropia)

EQ. DI STATO dipendono dal tipo di fluido d'interesse

- per i vapori: diagramma di MOLLIER
- gas perfetti: $pv = RT$ $\quad [Pa]\,[m^3/kg] = [J/kgK]\,[K]$
  - $R = \dfrac{\mathcal{R}}{\mu} \quad \dfrac{(8314\ J/kmol\,K)}{(kg/kmol)}$

$c_p - c_v = R$

$k = c_p/c_v$

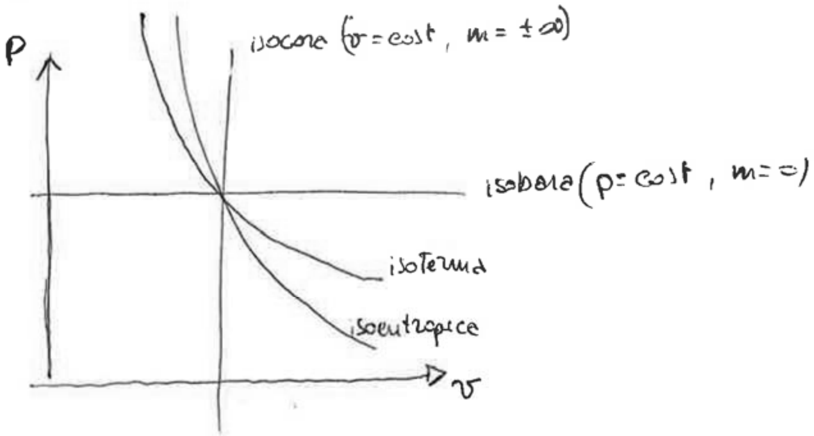
gas perfetti: → ideali ⇒ $c = cost$
→ quasi ideali ⇒ $c = c(T)$

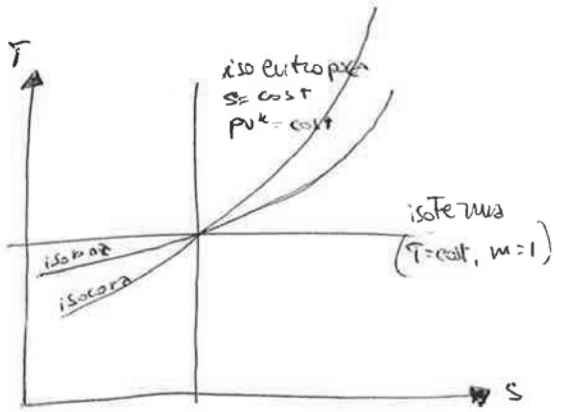
$$\boxed{\rho = \frac{1}{v} = \frac{p}{RT}} \qquad \text{gas} \rightarrow \rho(T)$$

- liquidi → $\boxed{\rho = \frac{1}{v} = cost}$

Evoluzione politropica → $p\,v^{m} = cost$ (m → esponente politropica)
→ $\delta Q = c\,dT$

politropiche notevoli





Nome	equazione	m	c
generica	$pv^m = cost$	m	c
isobara	$p = cost$	0	c_p
isocora	$v = cost$	$\pm\infty$	c_v
isoterma	$T = cost$	1	$\pm\infty$
isoentropica	$s = cost$	k	0

$$c = c_v \frac{m-k}{m-1}$$

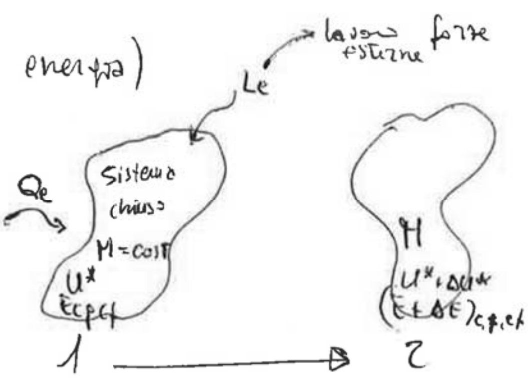
$$m = \frac{c_p - c}{c_v - c}$$

$$\boxed{pv^m = cost} + \boxed{pv = RT} = $$

$$= \frac{T}{p^{\frac{m-1}{m}}} = cost \; ; \quad T v^{m-1} = cost$$

I principio termodinamica (conserv. energia)

- punto di vista sostanziale
  approccio LAGRANGIANO
  I princ. per SISTEMI CHIUSI



$$Q_e + L_e = \Delta U^* + \Delta E_{c,g,cf}$$

$\to \Delta E_c + \Delta E_g + \Delta E_{cf}$

$\to \Delta U + \Delta U_{ch}$

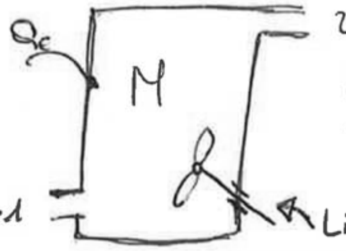
ΔU: ener. interna; ΔU_{ch}: energ. chimica (se il sistema non è reagente vale zero)

$$L_e = -\int_1^2 p\,dv + L_w + \Delta E_{c,g,cf}$$

$L_w \to$ lavoro delle resistenze passive

$$\Rightarrow Q_e = \Delta U^* + \int_1^2 p\,dv - L_w$$

- punto di vista locale / approccio EULERIANO / sistemi aperti



$L_i \to$ lavoro forze interne

Superficie di controllo rigida $\to \Delta L_e = 0$, $\Delta Q_e \neq 0$

$$\sum \dot m_1 = \sum \dot m_2$$

MOTO PERMANENTE / regime stazionario $\to$ non ho dipendenza tempor.

~~[illegible]~~

2 LEZIONE 30/09

ENTALPIA

I° principio, sistemi aperti:

$$Q_e + L_i = \Delta E_{c,g,cf} + \Delta i^*$$

$\Delta i^* \to \Delta i + (\Delta i_{CH} = \Delta u_{CH})$

$$L_i = \int_1^2 v\,dp + L_w + \Delta E_{cg,cf}$$

$$Q_e = \Delta i^* - \int_1^2 v\,dp - L_w$$

[Spesso parleremo di calori, lavori scambiati, energie etc... per unità di massa.]

LEGGE DI EVOLUZIONE D'ENERGIA (II Principio)

$$\underbrace{\delta Q_e + \delta L_w}_{\delta Q} = T dS \qquad \delta Q = c\, dT$$

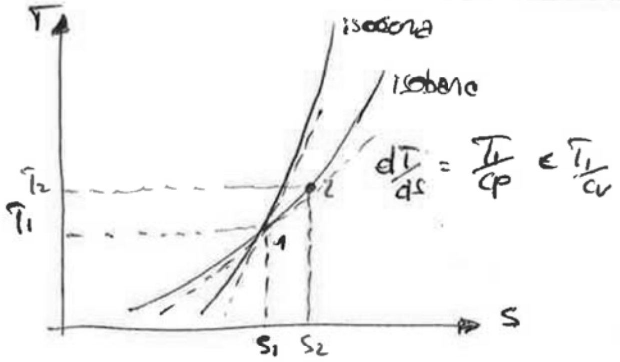
$$\Rightarrow \delta Q = c dT = \delta Q_e + \delta L_w = T ds$$

Nel caso di isoentropica $ds = 0 \vee c = 0 \Rightarrow \delta Q = 0 = \delta Q_e + \underbrace{\delta L_w}_{\geq 0} \Rightarrow \delta Q_e \leq 0$

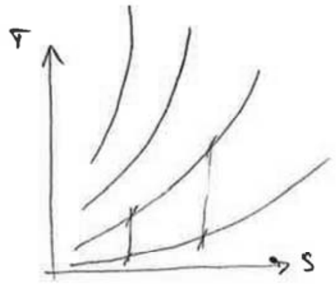
↳ caso processo REVERSIBILE $\Rightarrow L_w = 0 \Rightarrow \delta Q_e = 0$

ISOENTROPICA ≡ ADIABATICA REVERSIBILE

$$\frac{dT}{ds} = \frac{T}{c}$$



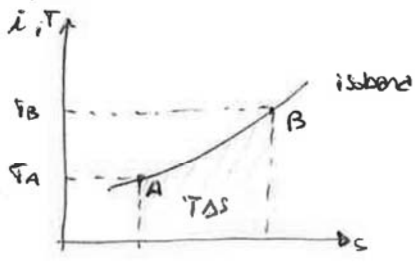
isocora o isobara sono monotone crescenti.



le isocore, o isobare sono delle curve divergenti!

$$\Delta U = c_v \Delta T$$
$$\Delta i = c_p \Delta T$$

$Hp: c_p = cost \Rightarrow \Delta i = c_p \Delta T$



I $\quad Q_e + \underbrace{L_i}_{=0} = \Delta i^* + \underbrace{\Delta E_{cgcf}}_{=0}$

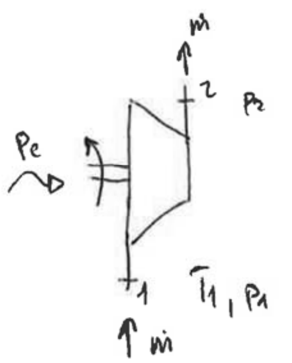
$\cancel{\Rightarrow Q_e = c_p(T_B - T_A)}$

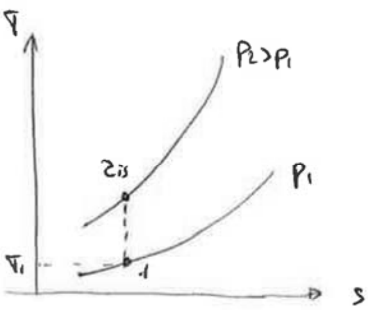
$Q_e = c_p(T_B - T_A)$

II $\quad Q = Q_e + \underbrace{L_w}_{=0} = \int_A^B T\, ds$

$$Q_e = c_p(T_B - T_A) = \int_A^B T\, ds$$

FENOMENO DI CONTRORECUPERO (in compressione)





$$\overset{\approx 0}{Q_e} + L_i = \Delta i\Big|_1^2 + \Delta E_c\Big|_1^2 + \Delta E_g\Big|_1^2 + \Delta E_f\Big|_1^2$$

ADIAB.

se ρ è piccola (aria) ≈ 0

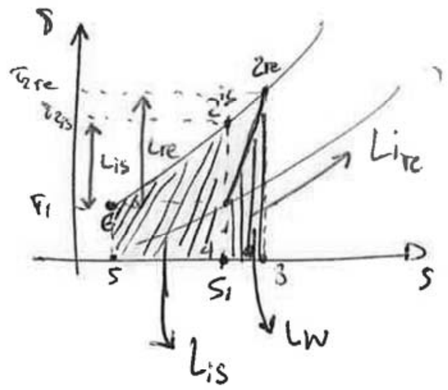
$v_1 \approx v_2 \Rightarrow \Delta E_c = 0$

≈ 0

03/10 3 LEZIONE

$$\Rightarrow L_i = \Delta i \Big|_1^2 \Rightarrow L_i = c_p(T_2 - T_1)$$

$$\underbrace{Q_e}_{0} + L_w = \int_1^2 T\,ds \Rightarrow L_w = \int_1^2 T\,ds$$



$$L_i = \int_1^2 v\,dp + L_w + \cancel{\Delta E_{c,p,g}}_0$$

$$\Rightarrow L_i - L_w = \int_1^2 v\,dp$$

Hp: il gas segue una politropica $\Rightarrow p v^m = \text{cost}$

$$\Rightarrow \int_1^2 v\,dp = \frac{m}{m-1} R T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} - 1\right]$$

compress. ideale ($m = k$) $\quad L_{i_{is}} = c_p(T_{2_{is}} - T_1) \quad 1 \rightarrow 2is$

compress. reale $\quad L_{re} = c_p(T_{2_{re}} - T_1) \quad 1 \rightarrow 2re$

$$\Delta i \Big|_6^{2is} = \Delta i \Big|_1^{2is} \qquad \Delta i \Big|_6^{2re} = \Delta i \Big|_1^{2re}$$

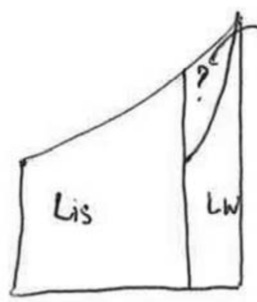
$$Q_e \Big|_6^{2is} = \int_6^{2is} T\,ds \qquad Q_e \Big|_6^{2re} = \int_6^{2re} T\,ds$$

$$L_{i_{re}} = \Delta i \Big|_1^{2re} = \Delta i \Big|_6^{2re} = Q_e \Big|_6^{2re} = \int_6^{2re} T\,ds \Rightarrow \text{Area } [5\ 6\ 2re\ 3]$$

$$L_{i_{is}} = \Delta i \Big|_1^{2is} = \Delta i \Big|_6^{2is} = Q_e \Big|_6^{2is} = \int_6^{2is} T\,ds \quad \text{Area } [5\ 6\ 2is\ 4]$$

$$L_{i_{re}} - L_{i_{is}} = \text{AREA } [4\ 2is\ 2re\ 3]$$

$$\underbrace{Q_e}_{=0} + L_w = \int_1^2 T\,ds$$



Lire

$\rightarrow$ Lavoro di controrecupero.

ne devo tenere conto quando il fluido in questione non è incomprimibile (tipo aria o altri gas)

$$\eta_{c_{is}} = \frac{L_{i_{is}}}{L_{i_{re}}} = \frac{\cancel{c_p}(T_{2_{is}} - T_1)}{\cancel{c_p}(T_{2_{re}} - T_1)}$$

$$\frac{T_{2is}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}}$$

$\boxed{\text{RENDIMENTO ISOENTROPICO}}$

$$\Rightarrow \eta_{c_{is}} = \frac{\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]}{\left[\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} - 1\right]}$$

$p_2/p_1 = \beta$ rapporto di compressione

$$L_{i_{re}} = \frac{L_{i_{is}}}{\eta_{c_{is}}} = \frac{c_p T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]}{\eta_{c_{is}}}$$

Rendimento IDRAULICO (politropico) di compressione

$$\eta_{y,c} = \frac{L_{i_{re}} - L_W}{L_{i_{re}}}$$

$H_p \approx$ fluido incomprimibile

idr.

$$= \frac{\int_1^2 v\,dp}{L_i} = \frac{\frac{m}{m-1} R \cancel{T_1} \cancel{\left[\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} - 1\right]}}{c_p \cancel{T_1} \cancel{\left[\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} - 1\right]}}$$

$c_p - c_v = R$

$c_p / c_v = k$

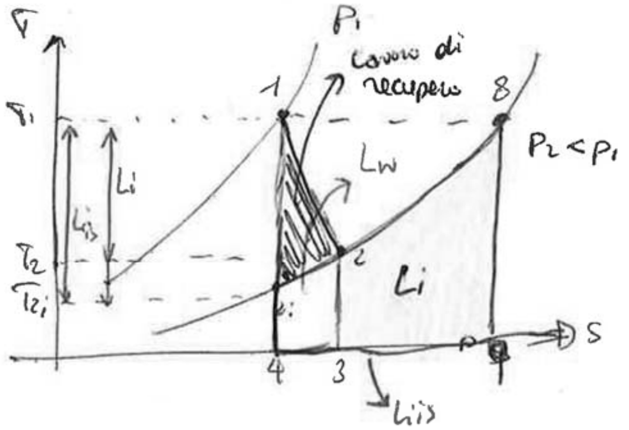
$$\Rightarrow c_p = R\left(\frac{k}{k-1}\right) \Rightarrow \Bigg] \Rightarrow \frac{\frac{m}{m-1} \cancel{R}}{\frac{k}{k-1} \cancel{R}} =$$

$$\eta_{y,c} = \left(\frac{m}{m-1}\right) \Big/ \left(\frac{k}{k-1}\right) \Rightarrow \frac{m-1}{m} = \frac{1}{\eta_{y,c}} \frac{k-1}{k}$$

$$L_i = c_p T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{1}{\eta_{y,c}}\frac{k-1}{k}} - 1\right]$$

$\rightarrow \frac{m-1}{m}$

LAVORO DI RECUPERO



$L_{is} = c_p (T_{2is} - T_1)$ AREA [4 2is 8 9]

$L_i = c_p (T_2 - T_1)$ AREA [3 2 8 9]

$$\eta_{is_t} = \frac{L_i}{L_{is}}$$

$$L_W = \int_1^2 T\,ds$$

$L_{is} - L_i < L_W$

$L_{is} - L_i = L_W - L_R$

$$\eta_{y,t} = \left(\frac{k}{k-1}\right) \Big/ \left(\frac{m}{m-1}\right) \Rightarrow \frac{m-1}{m} = \eta_{y,t} \frac{k-1}{k} \Rightarrow$$

$$\Rightarrow L_i = c_p T_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{-\eta_{y,t}\frac{k-1}{k}}\right] \qquad \beta_t = p_1/p_2$$

06/10 1° ESERCITAZIONE

4)

$c_p = 1004{,}5\ J/kg\,K$

$k = 1.4$

$p_1 = 1$ bar

$T = 17\ °C$

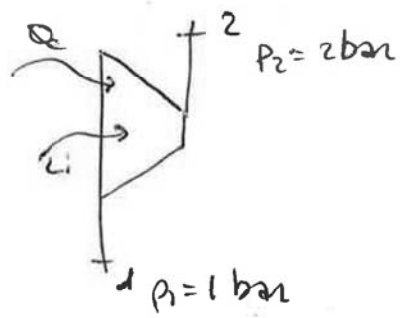
$p_2 = 2$ bar

$\Delta E_c \approx 0$

$L_i = ?$

$Q_e = ?$ per le trasf. elencate

$L_e = ?$



a) adiabatica reversibile

b) adiabatica irr con attriti η_{is} $m = 1.55$ — L_{cr}? L_{cc}?

c) refrigerazione senza attrito $m = 1.28$

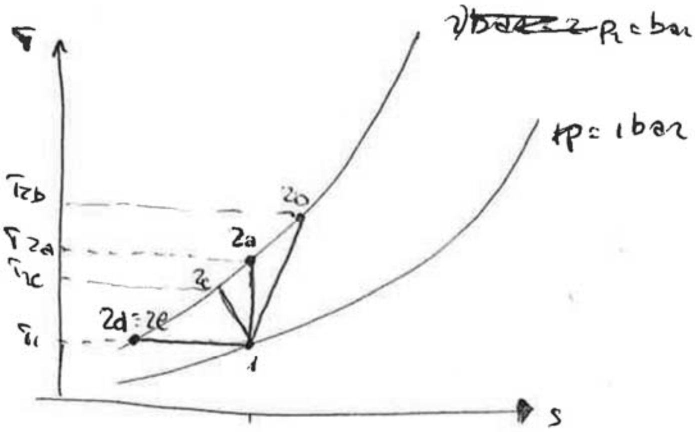
d) raffredd. isotermo senza attriti

e) raffredd. isotermo con attrito $L_W = 15{,}9\ kJ/kgK$

$Q_e + L_i = \Delta i = c_p (T_2 - T_1)$

a) $Q_e = 0 \Rightarrow L_i = c_p (T_2 - T_1)$

$L_W = 0 \Rightarrow$



a) ~~Reale~~ IDEALE

$$T_1 \, p_2^{\frac{k-1}{k}} = T_2 \, p_1^{\frac{k-1}{k}}$$

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = 353.3\,k$$

$$\Rightarrow L_{ia} = 63.8\ kJ/kg$$

REALE

b) $m = 1.55 \Rightarrow T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} = \cancel{365,4\,k}\ 370,9\,K$

$L_w > 0$

$Q_e = 0$

$$L_{ib} = c_p(T_{2b} - T_1) = 81,3\ kJ/kg$$

$\cancel{L_w = L_{ib} - L_{ia}}$

$$L_{ib} = \int_1^{2b} v\,dp + L_w \Rightarrow L_w = L_i - \int_1^{2b} v\,dp \Rightarrow$$

$$\int_1^{2b} v\,dp \rightarrow \frac{m}{m-1} R(T_{2b} - T_1)$$

$$\Rightarrow L_w = L_{ib} - 65,4\ kJ/kg =$$

$$= 15,9\ kJ/kg$$

$L_{i_b} - L_w = \int_1^{2b} v\,dp = 65,4\ kJ/kg$

$L_{ia} = 63,8\ kJ/kg$

$\Big\}\ (L_{i_b} - L_w) - L_{ia} = \boxed{1.6\ kJ/kg}$ lavoro di controrecupero

$$\eta_{is} = \frac{L_{ia}}{L_{ib}} = 0,785 \Rightarrow 78.5\%$$

$$\eta_y = \cancel{\frac{L_{ia} + L_{cr}}{L_{ib}}}\ \frac{L_{ib} - L_{wb}}{L_{ib}} = 0.804 \Rightarrow 80.4\%$$

c) refrigerazione senza attrito ($m = 1.28$)

$Q_e \neq 0 \quad L_w = 0 \qquad Q_e + L_i = \Delta i = c_p(T_{2c} - T_1)$

$$T_2 = \left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} T_1 = 337,5\,k$$

$$L_i = \int_1^2 v\,dp + \underbrace{L_w}_{0} = \frac{m}{m-1} R(T_{2c} - T_1) = 62,3\ kJ/kg$$

$$Q_e = \Delta i - L_i = \underbrace{c_p(T_{2c} - T_i)}_{47,5} - L_i = -14,8\ kJ/kg$$

d) raffreddamento isotermo senza attriti

↳ $Q_e < 0$ ↳ $T_{2d} = T_1$ ↳ $L_w = 0$

$$L_i = \int_1^{2d} v\,dp \qquad v = \frac{RT}{p} \Rightarrow L_i = RT_1 \int_1^{2d} \frac{dp}{p} = RT_1 \ln\left(\frac{P_2}{P_1}\right) = 57,7 \text{ kJ/kg}$$

$$Q_e - L_i = \underbrace{\Delta i}_{0} \Rightarrow Q_e = -57,7 \text{ kJ/kg}$$

e) raffreddamento isotermo con attriti ($L_w = 15.9$ kJ/kg)

$$L_{ie} = \underbrace{\int_1^{2e} v\,dp}_{57.5} + L_w \Rightarrow 73.9 \text{ kJ/kg} \Rightarrow Q_e = -73.9 \text{ kJ/kg}$$

Il compressore isotermo è quasi impossibile dal punto di vista pratico

5) $P_4 = 400$ kPa

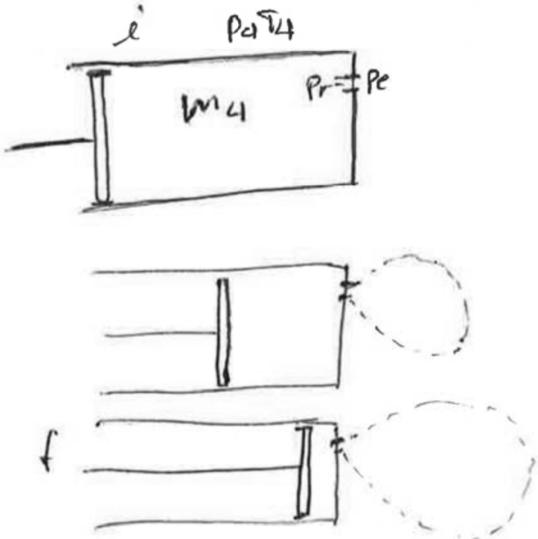
$T_4 = 1500$ K

$P_e = 110$ kPa

$Q_e = 0$ (Hp: adiab)

Hp: $k = 1.4$

Hp: $L_w \approx 0$



$$Q_e^{\,0} + L_e = \Delta U + \Delta E_c^{\,0} + \Delta E_p^{\,0} + \Delta E_{ch}^{\,0} \; [\text{kJ}]$$ vale anche quando l'aria esce fuori

$\Delta U = c_v (T_f - T_4)\, m$

$L_e = L_{est} + L_{e_{int}}$

$L_{e_{int}} = \int_i^f p\,dV - L_w - \cancel{\Delta E_{cg}} = P_e \Delta V$ ($0 - V_4$)

$L_{est} = \int_i^f p\,dV = P_e (V_f - 0)$

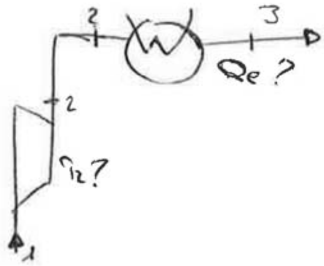
$L_e = P_e V_f - P_r V_4 = \Delta U$

$V_4 = \frac{mRT_4}{P_r} \qquad V_f = \frac{mRT_f}{P_e}$

$$c_v (T_f - T_4)\cancel{m} = \cancel{P_e} \frac{\cancel{m}RT_f}{\cancel{P_e}} - \cancel{P_r} \frac{\cancel{m}RT_4}{\cancel{P_r}}$$

$$c_v (T_f - T_4) = R (T_f - T_4)$$

ESERCIZIO 1



$Q_e + L_i = \Delta i + \underset{0}{\cancel{\Delta E_c}} + \underset{0}{\cancel{\Delta E_p}} + \underset{0}{\cancel{\Delta E_{cf}}}$

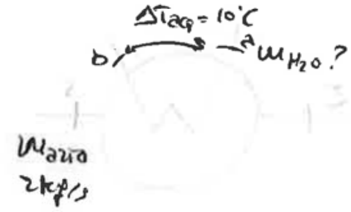
$\Big|_1^2 \underset{=0}{\cancel{Q_e}} + L_i = \Delta i$

$L_i = c_p(T_2 - T_1) \Rightarrow T_2 = 15 + \dfrac{65}{1.0045} = 79.5\,°C$

↳ trasf. is.

$\Big|_2^3 Q_e + \underset{=0}{\cancel{L_i}} = \Delta i \Rightarrow Q_e = c_p(T_3 - T_2) = 52.9\ kJ/kg$

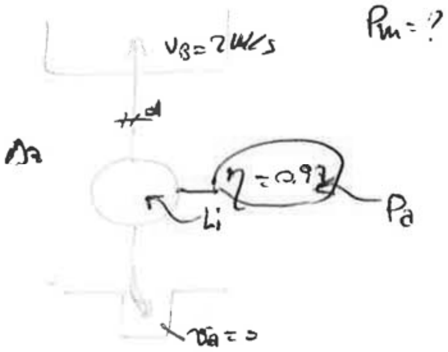
$\Big|_1^3 Q_e + L_i = \Delta i = c_p(T_3 - T_1)$



$\dot{Q} = Q_{e\,aria} \cdot m_{aria} = m_{H_2O}\, \dot{Q}_{H_2O} \Rightarrow m_{H_2O} = \dfrac{m_{aria}\, \dot{Q}_{e\,aria}}{Q_{acqua}} = 7.56\ kg/s$

↳ $\Big|_a^b \dot{Q}_{e\,H_2O} + L_i = \Delta i + \underset{0}{\cancel{\Delta E}} = c_{p_{H_2O}} \Delta T$

ES 2



$P_a = \dfrac{P_i}{\eta} = \dfrac{\dot{m} L_i}{\eta}$

$\Big|_a^b Q_e + L_i = \Delta i + \underset{0}{\cancel{\Delta E}} + \Delta E_c + \Delta E_p + \Delta E_{cf}$

Per risolvere l'esercizio: $L_i = \int_a^b v\,dp + L_w + \Delta E_c + \Delta E_p + \underset{0}{\cancel{\Delta E_{cf}}}$

$\Delta E_c \Big|_a^b = \dfrac{v_B^2 - v_a^2}{2}$ $\int_a^b v\,dp = \dfrac{1}{\rho}(P_B - \underset{=0}{P_A}) = 0$ $\rho = \dfrac{1}{v} = cost$

$\Delta E_p \Big|_a^b = g\Delta z$

$\Rightarrow L_i = 0 + L_w + \dfrac{v_b^2}{2} + g\Delta z$

caso 1) $L_w = 0 \Rightarrow L_i = 198.2\ J/kg$

caso 2) $L_w = \dfrac{15}{100} L_i \Rightarrow L_{ib} = 0.15 L_i + L_{ia} \Rightarrow L_{ib} = \dfrac{L_{ia}}{0.85} = 233.2\ J/kg$

$\dot{m} = \rho A v = 15.7\ kg/s \Rightarrow P_1 = \dfrac{\dot{m} L_{ia}}{\eta} = 3.2\ kW$

$P_2 = \dfrac{\dot{m} L_{ib}}{\eta} = 3.77\ kW$