



**UNIVERSITÀ DI PISA**  
FACOLTÀ di  
**INGEGNERIA**

## **APPLICAZIONI NUMERICHE**

|            |                    |
|------------|--------------------|
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| data:      | 16/01/2007         |

## APPLICAZIONE N°1



$l$  = lunghezza filo  
 $m$  = massa, peso  
 $g$  = accelerazione di gravità

Individuo le grandezze che possono avere influenza sul periodo d'oscillazione:

$$t = f(l, m, g)$$

Scrivo l'equazione come prodotto di potenze di tali grandezze:

$$t = C l^\alpha m^\beta g^\gamma$$

Scrivo le dimensioni fisiche di ogni grandezza

$$[C] = 1$$

$$[l] = L$$

$$[m] = M$$

$$[g] = L T^{-2}$$

$$[t] = T$$

sostituisco:

$$T = 1 \cdot L^\alpha M^\beta L^\gamma T^{-2\gamma}$$

da cui:

$$T) 1 = -2\gamma \rightarrow \gamma = -\frac{1}{2}$$

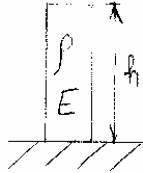
$$M) 0 = \beta$$

$$L) 0 = \alpha + \gamma \rightarrow \alpha = -\gamma = \frac{1}{2}$$

quindi:

$$t = C l^{\frac{1}{2}} m^0 g^{-\frac{1}{2}} = C \sqrt{\frac{l}{g}}$$

## APPLICAZIONE N°2



La frequenza propria di oscillazione della struttura rappresentata schematicamente dipende dall'altezza,  $h$ , dalla massa volumica,  $\rho$ , e dal modulo elastico,  $E$ .

$$f = f(h, \rho, E)$$

Procedendo analogamente all'esercizio precedente:

$$f = C h^\alpha \rho^\beta E^\gamma$$

$$[f] = T^{-1}$$

$$[C] = 1$$

$$[h] = L$$

$$[\rho] = M L^{-3}$$

$$[E] = \text{forza} \cdot L^{-2} = M L^{-1} T^{-2}$$

da cui:

$$T^{-1} = 1 \cdot L^\alpha M^\beta L^{-3\beta} M^\gamma L^{-\gamma} T^{-2\gamma}$$

$$T^{-1} - 1 = -2\gamma \rightarrow \gamma = \frac{1}{2}$$

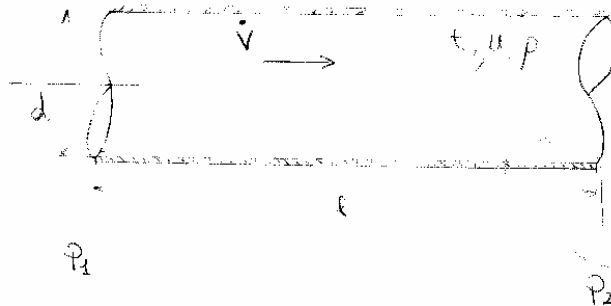
$$L) 0 = \alpha - 3\beta - \gamma \rightarrow \alpha = 3\beta + \gamma = -\frac{3}{2} + \frac{1}{2} = -1$$

$$M) 0 = \beta + \gamma \rightarrow \beta = -\gamma = -\frac{1}{2}$$

quindi

$$f = C h^{-1} \rho^{-\frac{1}{2}} E^{\frac{1}{2}} = C \frac{1}{h} \sqrt{\frac{E}{\rho}}$$

### APPLICAZIONE N°3



$$l = 25 \text{ m}$$

$$d = 13 \text{ cm}$$

$$e = 520 \text{ } \mu\text{m}$$

$$\dot{V} = 1500 \frac{\text{l}}{\text{min}}$$

$$t = 40^\circ\text{C}$$

$$\mu = 1,25 \text{ cP}$$

$$\rho_{\text{H}_2\text{O}} = 1000 \frac{\text{kg}}{\text{m}^3}$$

$$N_{\text{Re}} = ?$$

$$\Delta P = ?$$

$$N_{\text{Re}} = \frac{\rho c l}{\mu}$$

$$\dot{V} = c S \Rightarrow c = \frac{\dot{V}}{S} = \frac{\dot{V}}{\frac{\pi}{4} d^2}$$

da cui:

$$N_{\text{Re}} = \frac{\rho l \dot{V}}{\mu \frac{\pi}{4} d^2}$$

| Grandezze | SI                                                             | C.G.S.                                                         | sistema tecnico                                                                                    |
|-----------|----------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| $\rho$    | $1000 \frac{\text{kg}}{\text{m}^3}$                            | $1 \frac{\text{g}}{\text{cm}^3}$                               | $\frac{10^3}{981} \cdot 10194 \frac{\text{kgf} \cdot \text{s}^2}{\text{m}^4}$                      |
| $\mu$     | $1,25 \cdot 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}}$ | $1,25 \cdot 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{s}}$ | $\frac{1,25 \cdot 10^{-5}}{981} = 1,27 \cdot 10^{-4} \frac{\text{kgf} \cdot \text{s}}{\text{m}^2}$ |
| $l$       | 25 m                                                           | $25 \cdot 10^2 \text{ cm}$                                     | 25 m                                                                                               |
| $d$       | $13 \cdot 10^{-2} \text{ m}$                                   | 13 cm                                                          | $13 \cdot 10^{-2} \text{ m}$                                                                       |
| $\dot{V}$ | $25 \cdot 10^{-3} \frac{\text{m}^3}{\text{s}}$                 | $25 \cdot 10^3 \frac{\text{cm}^3}{\text{s}}$                   | $\frac{1800}{60} \cdot 10^{-3} = 25 \cdot 10^{-3} \frac{\text{m}^3}{\text{s}}$                     |

S.I.

$$N_{Re} = \frac{10^3 \frac{\text{kg}}{\text{m}^3} \cdot 25 \text{ m} \cdot 25 \cdot 10^{-3} \frac{\text{m}^3}{\text{s}}}{1,25 \cdot 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}} \cdot \frac{\pi}{4} \cdot (13 \cdot 10^{-2})^2 \text{ m}^2} = 3,77 \cdot 10^7$$

C.G.S.

$$N_{Re} = \frac{1 \frac{\text{g}}{\text{cm}^3} \cdot 25 \cdot 10^2 \text{ cm} \cdot 25 \cdot 10^3 \frac{\text{cm}^3}{\text{s}}}{1,25 \cdot 10^{-2} \frac{\text{g}}{\text{cm} \cdot \text{s}} \cdot \frac{\pi}{4} \cdot (13)^2 \text{ cm}^2} = 3,77 \cdot 10^7$$

Sistema tecnico

$$N_{Re} = \frac{101,94 \frac{\text{kgf} \cdot \text{s}^2}{\text{m}^4} \cdot 25 \text{ m} \cdot 25 \cdot 10^{-3} \frac{\text{m}^3}{\text{s}}}{1,27 \cdot 10^{-4} \frac{\text{kgf} \cdot \text{s}}{\text{m}^2} \cdot \frac{\pi}{4} \cdot (13 \cdot 10^{-2})^2 \text{ m}^2} = 377 \cdot 10^5 = 3,77 \cdot 10^7$$

Per il calcolo di  $|\Delta P|$  utilizzo il teorema  $\pi$  di Buckingham

$$|\Delta P| = f(l, d, e, c, \rho, \mu)$$

$$\pi = f(\pi_1, \pi_2)$$

$$\frac{|\Delta P|}{\rho} = f(d, e, c, \rho, \mu)$$

scelgo il set ricorrente:  $(d, c, \rho)$

$$\pi = \frac{|\Delta P|/\rho}{d^\alpha c^\beta \rho^\gamma}$$

$$[|\Delta P|] = M L T^{-2} L^{-2} = M L^{-1} T^{-2}$$

$$[l] = L$$

$$[d] = L$$

$$[c] = L T^{-1}$$

$$[\rho] = M L^{-3}$$

$$M L^{-1} T^{-2} L^{-1} = L^\alpha L^\beta T^{-\beta} M^\gamma L^{-3\gamma}$$

$$M) 1 = \gamma$$

$$L) -2 = \alpha + \beta - 3\gamma \rightarrow \alpha = 3\gamma - 2 - \beta = 3 - 2 - 2 = -1$$

$$T) -2 = -\beta \rightarrow \beta = 2$$

$$\pi = \frac{|\Delta P|/\rho}{d^{-1} c^2 \rho} = \frac{|\Delta P|}{\rho} \frac{d}{c^2 \rho}$$

$$\pi_1 = \frac{e}{d^\alpha c^\beta \rho^\gamma}$$

$$[e] = L$$

$$L = L^{\alpha_1} L^{\beta_1} T^{-\beta_1} M^{\gamma_1} L^{-3\gamma_1}$$

$$L) 1 = \alpha_1 + \beta_1 - 3\gamma_1 \rightarrow \alpha_1 = 1$$

$$T) 0 = -\beta_1$$

$$M) 0 = \gamma_1$$

$$\pi_1 = \frac{e}{d} = \varepsilon \rightarrow \text{rugosità relativa}$$

$$\pi_2 = \frac{\mu}{d^{\alpha_2} c^{\beta_2} \rho^{\gamma_2}}$$

$$[\mu] = M L^{-1} T^{-1}$$

$$M L^{-1} T^{-1} = L^{\alpha_2} L^{\beta_2} T^{-\beta_2} M^{\gamma_2} L^{-3\gamma_2}$$

$$M) 1 = \gamma_2$$

$$L) -1 = \alpha_2 + \beta_2 - 3\gamma_2 \rightarrow \alpha_2 = 3\gamma_2 - 1 - \beta_2 = 3 - 1 - 1 = 1$$

$$T) -1 = -\beta_2 \rightarrow \beta_2 = 1$$

$$\pi_2 = \frac{\mu}{d c \rho} = \frac{1}{N_{Re}}$$

da cui:

$$\frac{|\Delta P|}{l} \frac{d}{\rho c^2} = f(N_{Re}, \varepsilon) = f$$

$$\frac{|\Delta P|}{l} \frac{d}{\rho c^2} = f \Rightarrow |\Delta P| = f \frac{l \rho c^2}{d} = f \frac{l}{d} \rho \left( \frac{\dot{V}}{\frac{\pi}{4} d^2} \right)^2 = f \frac{l}{d^5} \frac{\rho (\dot{V})^2}{\left( \frac{\pi}{4} \right)^2}$$

f lo legge dal grafico

$$f\left(3,77 \cdot 10^7, \frac{e}{d} = \frac{520 \cdot 10^{-6} \text{ m}}{13 \cdot 10^{-2} \text{ m}} = 0,004\right) = 0,0072$$

$$|AP| = 0,0072 \cdot \frac{25 \text{ m} \cdot 10^3 \frac{\text{kg}}{\text{m}^3} (25 \cdot 10^{-3})^2 \frac{\text{m}^6}{\text{s}^2}}{(13 \cdot 10^{-2})^5 \text{ m}^5 \left(\frac{11}{4}\right)^2} = 4911,97 \text{ Pa}$$

#### APPLICAZIONE N°4

$$m_F = 200 \text{ g}$$

$$CS_F = 200 \frac{\text{g}}{\text{kWh}} = 200 \cdot 10^{-3} \frac{\text{kg}}{\text{kWh}}$$

$$h_c^F \cong 10000 \frac{\text{kcal}}{\text{kg}} \rightarrow \text{combustibili liquidi}$$

$$\eta = \frac{1}{CS_F h_c^F} = \frac{860}{200 \cdot 10^{-3} \cdot 10^4} = 0,43$$

#### APPLICAZIONE N°5

$$CS_Q = 2000 \frac{\text{kcal}}{\text{kWh}}$$

$$\eta = \frac{1}{CS_Q} = \frac{860}{2000} = 0,43$$

Essendo un motore a vapore, un rendimento plausibile può essere:

$$\eta = 0,30$$

$$CS_Q = \frac{1}{\eta} = \frac{860}{0,3} = 2866,7 \frac{\text{kcal}}{\text{kWh}}$$

#### APPLICAZIONE N°6

$$1) CS_Q = 14400 \frac{\text{kJ}}{\text{kWh}}$$

$$\eta = \frac{1}{CS_Q} = \frac{3600}{14400} = 0,25$$

$$2) CS_Q = 10000 \frac{\text{kJ}}{\text{kWh}}$$

$$\eta = \frac{1}{CS_Q} = \frac{3600}{10000} = 0,36$$

### APPLICAZIONE N° 7

Impianto (A)

$$CS_F = 0,364 \frac{\text{kg}}{\text{kWh}}$$

$$h_i^F = 41 \frac{\text{MJ}}{\text{kg}} = 9800 \frac{\text{kcal}}{\text{kg}}$$

$$\eta = \frac{1}{CS_F h_i^F} = \frac{860}{0,364 \cdot 9800} = 0,2551$$

Impianto (B)

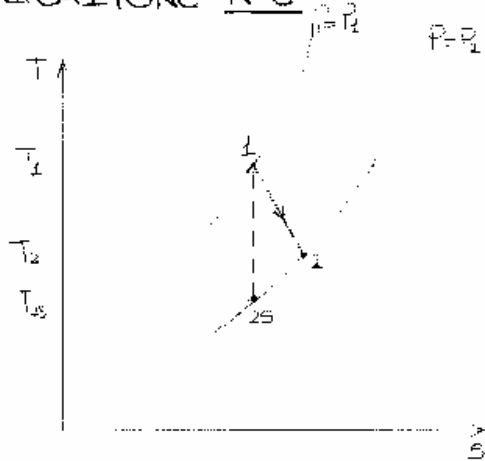
$$CS_F = 0,447 \frac{\text{kg}}{\text{kWh}}$$

$$h_i^F = 24 \frac{\text{MJ}}{\text{kg}} = 5732 \frac{\text{kcal}}{\text{kg}}$$

$$\eta = \frac{1}{CS_F h_i^F} = \frac{860}{0,447 \cdot 5732} = 0,3356$$

L' impianto con maggior rendimento è l'impianto B.

### APPLICAZIONE N° 8



stato 1)  $P_1 = 8 \text{ bar}$

$T_1 = 1000 \text{ K}$

stato 2)  $P_2 = 1,5 \text{ bar}$

$T_2 = 700 \text{ K}$

$m = 1 \text{ kg}$

①  $W_x = ?$

$$q - w_x = \Delta h + \cancel{\Delta e_k} + \cancel{\Delta e_p}$$

$= 0 \quad \quad \quad = 0 \quad \quad \quad = 0$

$$w_x = -\Delta h = h_1 - h_2$$

considero l'aria gas ideale:

$$w_x = h_1 - h_2 = c_p (T_1 - T_2) = \frac{1005 \text{ kJ}}{\text{kg K}} (1000 - 700) \text{ K} = 301,5 \frac{\text{kJ}}{\text{kg}}$$

$$W_x = m w_x = 1 \text{ kg} \cdot 301,5 \frac{\text{kJ}}{\text{kg}} = 301,5 \text{ kJ}$$

②  $\eta_{1s} = ?$

$$\eta_s = \frac{w_{x, \text{reale}}}{w_{x, \text{ideale}}} = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{c_p (T_1 - T_2)}{c_p (T_1 - T_{2s})}$$

essendo una trasformazione adiabatica:

$$\frac{T}{p^\gamma} = \text{cost.}$$

$$\frac{T_1}{p_1^\lambda} = \frac{T_{2s}}{p_{2s}^\lambda} \rightarrow T_{2s} = T_1 \left( \frac{p_{2s} = p_2}{p_1} \right)^\lambda = 1000 \text{ K} \left( \frac{1,5}{8} \right)^{\frac{1,4-1}{1,4}} = 620 \text{ K}$$

$$\eta_s = \frac{T_1 - T_2}{T_1 - T_{2s}} = \frac{(1000 - 700) \text{ K}}{(1000 - 620) \text{ K}} = 0,79$$

### APPLICAZIONE N° 9

Espansione adiabatica reversibile

$$\dot{m} = 10 \frac{\text{kg}}{\text{s}}$$

$$c_p = 1,1 \frac{\text{kJ}}{\text{kg K}}$$

$$k = 1,33$$

stato 1)  $p_1 = 8 \text{ bar}$

$$t_1 = 850^\circ\text{C}$$

$$C_1 = 10 \frac{\text{m}}{\text{s}}$$

$$z_1 = 3 \text{ m}$$

stato 2)  $p_2 = 1,1 \text{ bar}$

$$t_2 =$$

$$C_2 = 50 \frac{\text{m}}{\text{s}}$$

$$z_2 = 1 \text{ m}$$

$$\dot{W}_x = ?$$

$$\dot{W}_x = \dot{m} w_x$$

$$\dot{q} - w_x = \Delta h + \Delta e_k + \Delta e_p$$

$$= 0$$

$$w_x = -\Delta h - \Delta e_k - \Delta e_p = - (h_2 - h_1) - \frac{1}{2} (C_2^2 - C_1^2) - g(z_2 - z_1) =$$

$$= c_p (T_1 - T_2) + \frac{1}{2} (C_1^2 - C_2^2) + g(z_1 - z_2)$$

essendo una trasformazione adiabatica:

$$\frac{T}{p^\lambda} = \text{cost.}$$

$$\frac{T_1}{P_1^\lambda} = \frac{T_2}{P_2^\lambda} \rightarrow T_2 = T_1 \left( \frac{P_2}{P_1} \right)^\lambda = 1123 \text{ K} \left( \frac{1,1}{8} \right)^{\frac{1,33-1}{1,33}} = 686 \text{ K}$$

$$-\Delta h = c_p (T_1 - T_2) = 1,11 \frac{\text{kJ}}{\text{kg K}} (1123 - 686) \text{ K} = 485,07 \frac{\text{kJ}}{\text{kg}} = 485,07 \cdot 10^3 \frac{\text{m}^2}{\text{s}^2}$$

$$\Delta e_k = \frac{1}{2} (C_2^2 - C_1^2) = \frac{1}{2} (50^2 - 10^2) \frac{\text{m}^2}{\text{s}^2} = 1200 \frac{\text{m}^2}{\text{s}^2}$$

$$\Delta e_p = g(z_2 - z_1) = 9,81 \frac{\text{m}}{\text{s}^2} (1 - 3) \text{ m} = -19,62 \frac{\text{m}^2}{\text{s}^2}$$

→ sono trascurabili rispetto a  $\Delta h$

$$w_x = 485,07 \cdot 10^3 \frac{\text{m}^2}{\text{s}^2} - 1200 \frac{\text{m}^2}{\text{s}^2} + 19,62 \frac{\text{m}^2}{\text{s}^2} = 483,89 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{W}_x = \dot{m} w_x = 10 \frac{\text{kg}}{\text{s}} \cdot 483,89 \frac{\text{kJ}}{\text{kg}} \approx 4,84 \text{ MW}$$

### APPLICAZIONE N° 10

$$m = 1,5 \text{ kg}$$

$$P = \text{cost}$$

$$T_0 = 293 \text{ K}$$

$$T_1 = 260 \text{ K}$$

$$T_2 = T_0 = 293 \text{ K}$$

$$c_{p,ice} = 2,1 \frac{\text{kJ}}{\text{kg K}}$$

$$T_m = 273,15 \text{ K}$$

$$\Delta h_{3f} = 333,5 \frac{\text{kJ}}{\text{kg}}$$

$$c_{p,w} = 4,2 \frac{\text{kJ}}{\text{kg K}}$$

$$I = m i$$

$$i = T_0(s_2 - s_1) - q_0$$

Il fenomeno si può dividere in tre parti:

① RISCALDAMENTO GHIACCIO

$$\delta q_0^I = du = c_{p,ice} dT$$

$$q_0^I = \int \delta q_0^I = \int_{T_1}^{T_m} c_{p,ice} dT = c_{p,ice} (T_m - T_1) = 2,1 \frac{\text{kJ}}{\text{kg K}} (273,15 - 260) \text{ K} =$$

$$= 27,615 \frac{\text{kJ}}{\text{kg}}$$

$$ds^I = \frac{\delta q_0^I}{T} = c_{p,ice} \frac{dT}{T}$$

$$\Delta s^I = \int ds^I = \int_{T_1}^{T_m} c_{p,ice} \frac{dT}{T} = c_{p,ice} \ln \frac{T_m}{T_1} = 2,1 \frac{\text{kJ}}{\text{kg K}} \ln \frac{273,15 \text{ K}}{260 \text{ K}} = 0,104 \frac{\text{kJ}}{\text{kg K}}$$

II PASSAGGIO DI STATO

$$\delta q_o^{\text{II}} = dh$$

$$q_o^{\text{II}} = \Delta h_{s-f} = 333,5 \frac{\text{kJ}}{\text{kg}}$$

$$ds^{\text{II}} = \frac{\delta q_o^{\text{II}}}{T} = \frac{dh}{T}$$

$$\Delta s^{\text{II}} = \frac{\Delta h_{s-f}}{T_m} = \frac{333,5 \frac{\text{kJ}}{\text{kg}}}{273,15 \text{ K}} = 1,221 \frac{\text{kJ}}{\text{kg K}}$$

III RISCALDAMENTO ACQUA

$$\delta q_o^{\text{III}} = c_{p,w} dT$$

$$q_o^{\text{III}} = \int_{T_m}^{T_2=T_0} c_{p,w} dT = c_{p,w} (T_0 - T_m) = 4,2 \frac{\text{kJ}}{\text{kg K}} (293 - 273,15) \text{ K} = 83,370 \frac{\text{kJ}}{\text{kg}}$$

$$ds^{\text{III}} = \frac{\delta q_o^{\text{III}}}{T} = c_{p,w} \frac{dT}{T}$$

$$\Delta s^{\text{III}} = \int_{T_m}^{T_2=T_0} \frac{c_{p,w} dT}{T} = c_{p,w} \ln \frac{T_0}{T_m} = 4,2 \frac{\text{kJ}}{\text{kg K}} \ln \frac{293}{273,15} = 0,295 \frac{\text{kJ}}{\text{kg K}}$$

$$q_o = q_o^{\text{I}} + q_o^{\text{II}} + q_o^{\text{III}} = (27,615 + 333,5 + 83,370) \frac{\text{kJ}}{\text{kg}} = 444,485 \frac{\text{kJ}}{\text{kg}}$$

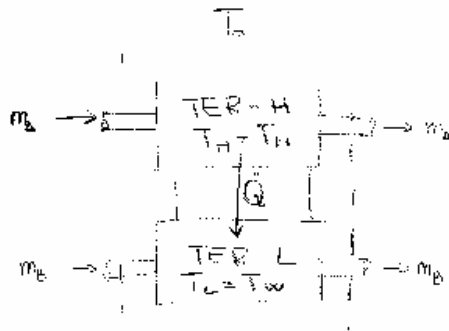
$$\Delta s = s_2 - s_1 = \Delta s^{\text{I}} + \Delta s^{\text{II}} + \Delta s^{\text{III}} = (0,106 + 1,221 + 0,295) \frac{\text{kJ}}{\text{kg K}} = 1,620 \frac{\text{kJ}}{\text{kg K}}$$

$$i = T_0 \Delta s - q_o = 293 \text{ K} \cdot 1,620 \frac{\text{kJ}}{\text{kg K}} - 444,485 \frac{\text{kJ}}{\text{kg}} = 30,175 \frac{\text{kJ}}{\text{kg}}$$

$$I = m i = 1,5 \text{ kg} \cdot 30,175 \frac{\text{kJ}}{\text{kg}} = 45,263 \text{ kJ}$$

Tale irreversibilità rappresenta il valore assoluto del minimo lavoro che bisognerebbe spendere per riportare l'acqua nello stato iniziale, utilizzando un frigorifero ideale, ovvero un frigorifero che segua un ciclo di Carnot inverso.

### APPLICAZIONE N°11



$$\dot{Q} = 500 \text{ MW}$$

$$T_0 = 290 \text{ K}$$

$$T_H = 590 \text{ K}$$

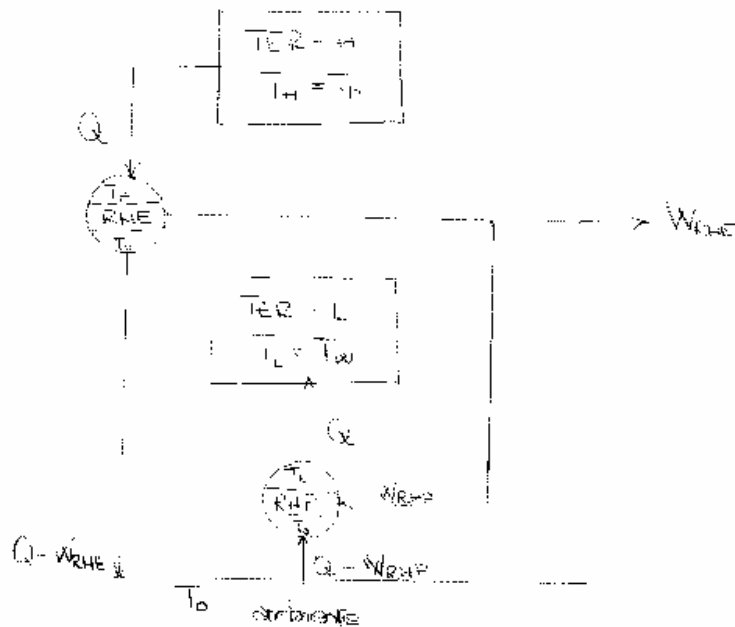
$$T_L = 550 \text{ K}$$

$$\dot{E}_A^Q = \dot{Q} \left( 1 - \frac{T_0}{T_H} \right) = \dot{Q} \left( 1 - \frac{T_0}{T_H} \right)$$

$$\dot{E}_B^Q = \dot{Q} \left( 1 - \frac{T_0}{T_L} \right) = \dot{Q} \left( 1 - \frac{T_0}{T_L} \right)$$

$$\dot{I} = \dot{E}_A^Q - \dot{E}_B^Q = \dot{Q} \left( 1 - \frac{T_0}{T_H} - 1 + \frac{T_0}{T_L} \right) = \dot{Q} T_0 \left( \frac{1}{T_L} - \frac{1}{T_H} \right) =$$

$$= 500 \text{ MW} \cdot 290 \text{ K} \left( \frac{1}{550 \text{ K}} - \frac{1}{590 \text{ K}} \right) = 17,87 \text{ MW}$$



### APPLICAZIONE N° 12

stato 1)  $P_1 = 2 \text{ bar}$   
 $T_1 = 393,15 \text{ K}$

stato ambiente)  $P_0 = 1 \text{ bar}$   
 $T_0 = 293,15 \text{ K}$

$E_{ph,1} = ?$

$$E_{ph,1} = \beta_1 - \beta_0 = (h_1 - h_0) - T_0(s_1 - s_0) = \bar{c}_p (T_1 - T_0) - T_0 \left[ \bar{c}_p \ln \frac{T_1}{T_0} - R \ln \frac{P_1}{P_0} \right] =$$

$$= \underbrace{\bar{c}_p \left[ T_1 - T_0 - T_0 \ln \frac{T_1}{T_0} \right]}_{E_{ph}^{\Delta T}} + \underbrace{RT_0 \ln \frac{P_1}{P_0}}_{E_{ph}^{\Delta P}}$$

$$E_{ph}^{\Delta T} = 1,005 \frac{\text{kJ}}{\text{kg K}} \left[ 393,15 - 293,15 \left( 1 + \ln \frac{393,15}{293,15} \right) \right] \text{K} = 14,028 \frac{\text{kJ}}{\text{kg}}$$

$$E_{ph}^{\Delta P} = R T_0 \ln \frac{P_1}{P_0} = 287 \frac{\text{J}}{\text{kg K}} \cdot 293,15 \text{ K} \ln \frac{2}{1} = 58,32 \frac{\text{kJ}}{\text{kg}}$$

$$E_{ph,1} = 14,028 \frac{\text{kJ}}{\text{kg}} + 58,32 \frac{\text{kJ}}{\text{kg}} = 72,35 \frac{\text{kJ}}{\text{kg}}$$

### APPLICAZIONE N° 13

stato 1)  $P_1 = 0,7 \text{ bar}$   
 $T_1 = 268,15 \text{ K}$

stato ambiente)  $P_0 = 1 \text{ bar}$   
 $T_0 = 293,15 \text{ K}$

$\text{CO}_2$ :  $\tilde{m} = 44,01 \frac{\text{g}}{\text{mol}} \rightarrow R = \frac{\tilde{R}}{\tilde{m}} = \frac{8,314 \frac{\text{J}}{\text{mol K}}}{44,01 \frac{\text{g}}{\text{mol}}} = 0,189 \frac{\text{J}}{\text{g K}} = 189 \frac{\text{J}}{\text{kg K}}$   
 $k = 1,3$

Analogamente all'esercizio precedente:

$$\begin{aligned} \epsilon_{ph}^{\Delta T} &= c_p \left[ T_1 - T_0 \left( 1 + \ln \frac{T_1}{T_0} \right) \right] = \frac{k}{k-1} R \left[ T_1 - T_0 \left( 1 + \ln \frac{T_1}{T_0} \right) \right] = \\ &= \frac{1,3}{1,3-1} 189 \frac{\text{J}}{\text{kg K}} \left[ 268,15 - 293,15 \left( 1 + \ln \frac{268,15}{293,15} \right) \right] \text{K} = 926,105 \frac{\text{J}}{\text{kg}} \end{aligned}$$

$$\epsilon_{ph}^{\Delta P} = R T_0 \ln \frac{P_1}{P_0} = 189 \frac{\text{J}}{\text{kg K}} \cdot 293,15 \text{ K} \ln \left( \frac{0,7}{1} \right) = -19761,7 \frac{\text{J}}{\text{kg}}$$

$$E_{ph,1} = \epsilon_{ph}^{\Delta T} + \epsilon_{ph}^{\Delta P} = (926,105 - 19761,7) \frac{\text{J}}{\text{kg}} = -18835,6 \frac{\text{J}}{\text{kg}} \approx -18,8 \frac{\text{kJ}}{\text{kg}}$$

### APPLICAZIONE N° 14

miscela:  $x_{\text{CO}} = 0,15$   
 $x_{\text{aria}} = 0,85$

$$\tilde{E}_{0,\text{CO}} = 275430 \frac{\text{kJ}}{\text{kmol}}$$

stato ambiente)  $P_0 = 1 \text{ bar}$   
 $T_0 = 298,15 \text{ K}$

$$\tilde{E}_{0,M} = \tilde{E}_{0,\text{CO}} x_{\text{CO}} + \tilde{E}_{0,\text{aria}} x_{\text{aria}} + \tilde{R} T_0 \left[ x_{\text{CO}} \ln x_{\text{CO}} + x_{\text{aria}} \ln x_{\text{aria}} \right]$$

$$\dot{\tilde{E}}_{0, \text{ARIA}} = 0$$

$$\begin{aligned}\dot{\tilde{E}}_{0, H} &= 275430 \frac{\text{kJ}}{\text{kmol}} \cdot 0,15 + 8,314 \frac{\text{kJ}}{\text{kmol K}} \cdot 298,15 \text{ K} [0,15 \ln 0,15 + 0,85 \ln 0,85] = \\ &= 40266,68 \frac{\text{kJ}}{\text{kmol}}\end{aligned}$$

### APPLICAZIONE N° 15

$$\dot{m} = 5 \frac{\text{kg}}{\text{s}}$$

$$c_p = 2,85 \frac{\text{kJ}}{\text{kg K}}$$

$$T_1 = 250 \text{ K}$$

$$T_2 = 253 \text{ K}$$

$$T_0 = 293 \text{ K}$$

$$\dot{I} = T_0 (\dot{\Delta S})_{\text{ISOLATO}}$$

$$(\dot{\Delta S})_{\text{ISOLATO}} = (\dot{\Delta S})_{\text{SYSTEMA}} - \frac{\dot{Q}_0}{T_0} = \dot{m}(s_2 - s_1) - \frac{\dot{Q}_0}{T_0}$$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} = c_p \ln \frac{T_2}{T_1}$$

$$\dot{Q}_0 = \dot{m} c_p (T_2 - T_1)$$

$$\Rightarrow \dot{I} = T_0 \dot{m} c_p \left[ \ln \frac{T_2}{T_1} - \frac{(T_2 - T_1)}{T_0} \right] =$$

$$= 293 \text{ K} \cdot 5 \frac{\text{kg}}{\text{s}} \cdot 2,85 \frac{\text{kJ}}{\text{kg K}} \left[ \ln \frac{253}{250} - \frac{(253 - 250)}{293} \right] = 7,05 \text{ kW}$$

Tale irreversibilità è dovuta a scambi di calore sotto  $\Delta T$  finiti e rappresenta il lavoro minimo da spendere per ripristinare la situazione iniziale, ovvero riportare la salomina alla temperatura  $T_1$ .

### APPLICAZIONE N° 16

$$m = 1 \text{ kg}$$

$$P_L = 0,05 \text{ bar}$$

$$P_H = 150 \text{ bar}$$

$$v = 10^{-3} \frac{\text{m}^3}{\text{kg}}$$

$$|W_x| = m |w_x|$$

$$\begin{aligned} \oint w_{x,p} &= \int_{P_L}^{P_H} -v dP = -v(P_H - P_L) = -10^{-3} \frac{\text{m}^3}{\text{kg}} (150 - 0,05) \text{ bar} \approx \\ &\approx -10^{-3} \frac{\text{m}^3}{\text{kg}} \cdot 150 \cdot 10^5 \text{ Pa} = -15 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

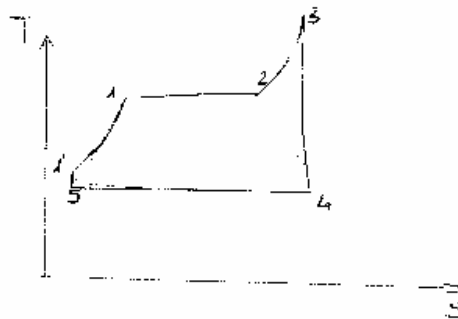
$$|W_x| = m |w_x| = 1 \text{ kg} \cdot 15 \frac{\text{kJ}}{\text{kg}} = 15 \text{ kJ}$$

### APPLICAZIONE N° 17

$$P_L = 0,05 \text{ bar}$$

$$P_H = 150 \text{ bar}$$

$$t_3 = 500^\circ\text{C}$$



$$\textcircled{a} \dot{W}_x = 300 \text{ MW}$$

$$\dot{W}_x = \dot{m}_v w_x \rightarrow \dot{m}_v = \frac{\dot{W}_x}{w_x}$$

$$w_x = w_{x,T} + w_{x,p} \approx w_{x,T}$$

$$\oint w_{x,T} = \Delta h_{3-4}$$

$$w_{x,T} = h_3 - h_4$$

dalle tabelle termodinamiche:

$$h_3 = 3310,6 \frac{\text{kJ}}{\text{kg}}$$

ricavo:

$$h_u = 1935,04 \frac{\text{kJ}}{\text{kg}}$$

$$w_x = h_3 - h_u = (3310,6 - 1935,04) \frac{\text{kJ}}{\text{kg}} = 1375,56 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{m}_v = \frac{\dot{W}_x}{w_x} = \frac{300 \cdot 10^3 \text{ kW}}{1375,56 \frac{\text{kJ}}{\text{kg}}} = 218 \frac{\text{kg}}{\text{s}}$$

(b)

$$\eta = \frac{w_x}{q_H} = \frac{h_3 - h_u + h_5 - h_{u'}}{h_3 - h_{u'}} = 1 - \frac{h_u - h_5}{h_3 - h_{u'}} = 1 - \frac{19,1}{q_H}$$

$$w_{x,p} \approx 0 \rightarrow h_5 \approx h_{u'} = 137,77 \frac{\text{kJ}}{\text{kg}}$$

$$\eta_p = 1 - \frac{(1935,04 - 137,77)}{(3310,6 - 137,77)} = 0,43$$

(c)

$$\eta = \frac{\dot{W}_x}{\dot{Q}_H} \rightarrow \dot{Q}_H = \frac{\dot{W}_x}{\eta} = \frac{300 \text{ MW}}{0,43} = 697,7 \text{ MW}$$

### APPLICAZIONE N°18

$$\begin{aligned} \bullet q &= \alpha + 1 - A = (1+e) \frac{m_b^{\text{stech}}}{m_F} + 1 - A = (1+e) \frac{100}{23,2} \frac{m_b^{\text{stech}}}{m_F} + 1 - A \\ \bullet h_i^F &= 7800 C + 28600 \left( H - \frac{O}{8} \right) + 2200 S - 600 U \\ \bullet T_c &= T_0 + \frac{\eta_c h_i^F}{q c_{mp}} (1 - \sigma) \end{aligned}$$

$$c_{p,f} = 0,3 \frac{\text{kcal}}{\text{kg K}} = 1,2552 \frac{\text{kJ}}{\text{kg K}}$$

③  $\text{CH}_4$  gassoso

$$C = 0,75$$

$$H = 0,25$$

$$e = 0,05$$

$$\frac{m_b^{\text{stech}}}{m_F} = \frac{8}{3} C + 8 H + S - O$$

$$\frac{m_b^{\text{stech}}}{m_F} = \frac{8}{3} \cdot 0,75 + 8 \cdot 0,25 = 4$$

$$\frac{m_b^{\text{stech}}}{m_F} = \frac{100}{23,2} \frac{m_b^{\text{stech}}}{m_F} = 4 \cdot \frac{100}{23,2} = 17,24$$

$$q = (1 + 0,05) 17,24 + 1 = 19,102$$

$$h_i^F = 7800 \cdot 0,75 + 28600 \cdot 0,25 = 13000 \frac{\text{kcal}}{\text{kg}} = 54392 \frac{\text{kJ}}{\text{kg}}$$

dalle tabelle:  $h_i^F = 50050 \frac{\text{kJ}}{\text{kg}}$

$$\sigma = 0, \quad \eta_c \approx 1$$

$$T_c = 293 \text{ K} + \frac{50050 \frac{\text{kJ}}{\text{kg}}}{19,102 \cdot 1,2552 \frac{\text{kJ}}{\text{kg K}}} = 2380 \text{ K}$$

$$\sigma = 0,2$$

$$T_c = 293 \text{ K} + \frac{50050 \frac{\text{kJ}}{\text{kg}}}{19,102 \cdot 1,2552 \frac{\text{kJ}}{\text{kg K}}} (1 - 0,2) = 1963 \text{ K}$$

$$\sigma = 0,4$$

$$T_c = 1545 \text{ K}$$

⑥ Benzina auto

$$e = 10\%$$

$$C = 0,85$$

$$H = 0,14$$

$$S = 0,01$$

$$\frac{m_o^{\text{fuel}}}{m_p} = \frac{8}{3} \cdot 0,85 + 8 \cdot 0,14 + 0,01 = 3,4$$

$$\frac{m_A^{\text{fuel}}}{m_p} = \frac{100}{23,2} \cdot 3,4 = 14,66$$

$$q = (1 + 0,1) 14,66 + 1 = 17,126$$

$$h_c^F = (7800 \cdot 0,85 + 28000 \cdot 0,14 + 22000 \cdot 0,01) \frac{\text{kJ}}{\text{kg}} = 10656 \frac{\text{kJ}}{\text{kg}} = 44585 \frac{\text{kJ}}{\text{kg}}$$

dalle tabelle:  $h_c^F = 44000 \frac{\text{kJ}}{\text{kg}}$

$$\sigma = 0 \rightarrow T_c = 293 \text{ K} + \frac{44000 \frac{\text{kJ}}{\text{kg}}}{17,126 \cdot 1,2552 \frac{\text{kJ}}{\text{kg K}}} = 2340 \text{ K}$$

$$\sigma = 0,2 \rightarrow T_c = 1930 \text{ K}$$

$$\sigma = 0,4 \rightarrow T_c = 1521 \text{ K}$$

③ carbone  $\epsilon \approx 35\%$

$$C = 0,748$$

$$H = 0,052$$

$$S = 0,033$$

$$N = 0,015$$

$$O = 0,067$$

$$U = 0,025$$

$$A = 0,07$$

$$\frac{m_b^{STECH}}{m_F} = \frac{8}{3} \cdot 0,748 + 8 \cdot 0,052 + 0,033 - 0,067 = 2,38$$

$$\frac{m_b^{STECH}}{m_F} = \frac{100}{23,2} \cdot 2,38 = 10,26$$

$$q = (1 + 0,3) \cdot 10,26 + 1 - 0,07 = 14,268$$

$$\begin{aligned} h_c^F &= \left( 7800 \cdot 0,748 + 28600 \left( 0,052 - \frac{0,067}{8} \right) + 2200 \cdot 0,033 - 600 \cdot 0,025 \right) \frac{\text{kcal}}{\text{kg}} = \\ &= 7140 \frac{\text{kcal}}{\text{kg}} = 29874 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

$$\sigma = 0 \rightarrow T_c = 293 \text{ K} + \frac{29874 \frac{\text{kJ}}{\text{kg}}}{14,268 \cdot 1,2852 \frac{\text{kJ}}{\text{kg K}}} = 1961 \text{ K}$$

$$\sigma = 0,2 \rightarrow T_c = 1627 \text{ K}$$

$$\sigma = 0,4 \rightarrow T_c = 1294 \text{ K}$$

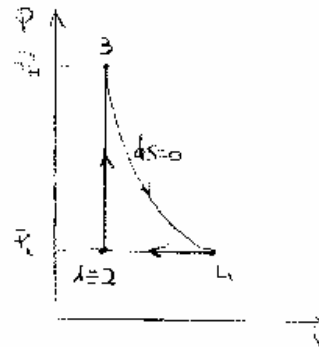
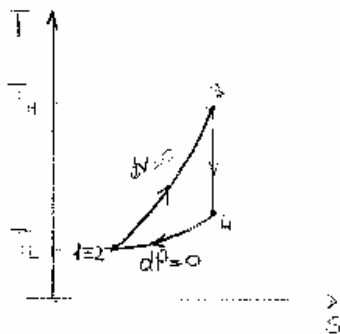
# APPLICAZIONE N° 19

$$k = 1,4$$

$$T_1 = 300 \text{ K}$$

$$T_3 = 2400 \text{ K}$$

## ③ CICLO LENOIR



$$\eta = 1 - \frac{|q_L|}{q_H}$$

$$q_H = \Delta u_{2-3} = c_v(T_3 - T_2)$$

$$|q_L| = -\Delta h_{4-1} = c_p(T_4 - T_1)$$

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

trasf. 1→3  $v = \text{cost}$

$$P_v = RT \Rightarrow \frac{P}{T} = \text{cost.}$$

$$\frac{P_3}{T_3} = \frac{P_1}{T_1} \Rightarrow \frac{T_3}{T_1} = \frac{P_3}{P_1} = \beta = \frac{2400 \text{ K}}{300 \text{ K}} = 8$$

~~trasf.~~

$$\frac{T_4}{T_1} = \frac{T_4}{T_3} \cdot \frac{T_3}{T_1}$$

trasf. 3 → 4

$$\frac{T_4}{P_4^\lambda} = \frac{T_3}{P_3^\lambda} \rightarrow \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^\lambda = \frac{1}{\beta^\lambda}$$

$$\frac{T_4}{T_1} = \frac{1}{\beta^\lambda} \cdot \beta = \beta^{\frac{1}{\kappa}}$$

$$\eta_L = 1 - \kappa \frac{\beta^{\frac{1}{\kappa}} - 1}{\beta - 1} = 1 - 1,4 \frac{8^{\frac{1}{1,4}} - 1}{8 - 1} = 0,32$$

$$\eta_L = \bar{\eta}_c = 1 - \frac{\bar{T}_L}{\bar{T}_H}$$

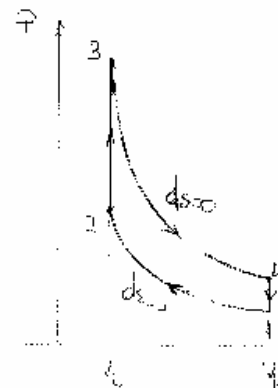
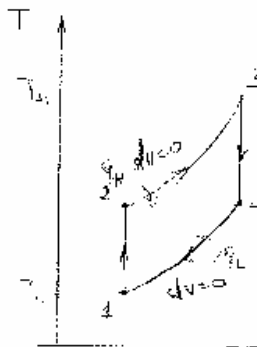
$$q_H = \bar{T}_H (s_3 - s_1) = c_v (T_3 - T_1)$$

$$s_3 - s_1 = c_p \ln \frac{T_3}{T_1} - R \ln \frac{P_3}{P_1} = c_v \ln \beta$$

$$\bar{T}_H = \frac{c_v (T_3 - T_1)}{c_v \ln \beta} = \frac{(2400 - 300) K}{\ln 8} = 1009,89 K$$

$$\bar{T}_L = \bar{T}_H (1 - \eta_L) = 1009,89 K (1 - 0,32) = 687 K$$

⑥ CICLO OTTO



$$p = 12 = \frac{v_1}{v_2} = \frac{v_4}{v_3} = \frac{v_1}{v_3} = \frac{v_4}{v_2}$$

$$\eta = 1 - \frac{|q_c|}{q_H}$$

$$q_H = c_v(T_3 - T_2)$$

$$|q_c| = c_v(T_4 - T_1)$$

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

traj. 1→2

$$T v^{k-1} = \text{cost.}$$

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

traj. 3→4

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

$$\frac{T_1}{T_2} = \frac{T_4}{T_3} \rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\eta_o = 1 - \frac{1}{p^{k-1}} = 1 - \frac{1}{12^{(1.4-1)}} = 0.63$$

$$\eta_o = \bar{\eta}_c = 1 - \frac{\bar{T}_c}{\bar{T}_H}$$

$$q_H = \bar{T}_H(s_3 - s_2) = c_v(T_3 - T_2)$$

$$s_3 - s_2 = c_p \ln \frac{T_3}{T_2} - R \ln \frac{p_3}{p_2}$$

trasf. 2 → 3  $v = \text{cost.}$

$$Pv = RT \rightarrow \frac{P}{T} = \text{cost.}$$

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \rightarrow \frac{P_3}{P_2} = \frac{T_3}{T_2}$$

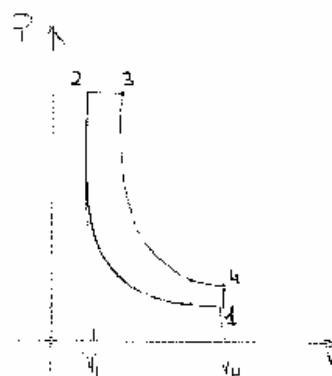
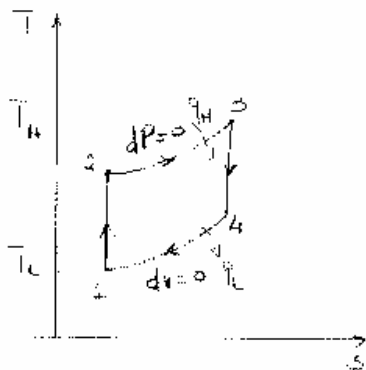
$$\bar{T}_H = \frac{q_H (T_3 - T_2)}{R \ln \frac{T_3}{T_2}}$$

$$T_2 = T_1 p^{k-1} = 300 \text{ K} \cdot 12^{(1,4-1)} = 810,58 \text{ K}$$

$$\bar{T}_H = \frac{(2400 - 810,58) \text{ K}}{\ln \frac{2400}{810,58}} = 1464 \text{ K}$$

$$\bar{T} = \bar{T}_H (1 - \eta) = 1464 \text{ K} (1 - 0,68) = 542 \text{ K}$$

### ③ CICLO DIESEL



$$p = 12 = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$

$$\text{introduco: } r_p = \frac{T_3}{T_2}$$

$$\eta = 1 - \frac{|q_L|}{q_H}$$

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

$$\frac{T_4}{T_2} = \left(\frac{v_2}{v_4}\right)^{k-1} = \frac{1}{\rho^{k-1}}$$

$$\frac{T_4}{T_2} = \frac{T_4}{T_3} \cdot \frac{T_3}{T_2} \cdot \frac{T_2}{T_1}$$

transf. 3 → 4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \left(\frac{v_3}{v_2} \cdot \frac{v_2}{v_4}\right)^{k-1}$$

transf. 2 → 3      $P = \text{cost.}$

$$\frac{v}{T} = \text{cost.}$$

$$\frac{v_3}{T_3} = \frac{v_2}{T_2} \rightarrow \frac{T_3}{T_2} = \frac{v_3}{v_2} = \gamma_p$$

$$\frac{T_4}{T_1} = \gamma_p^{k-1} \cdot \frac{1}{\rho^{k-1}} \cdot \gamma_p \cdot \rho^{k-1} = \gamma_p^k$$

$$\eta_D = 1 - \frac{1}{k} \frac{1}{\rho^{k-1}} \frac{\gamma_p^k - 1}{\gamma_p - 1}$$

$$T_2 = T_1 \rho^{k-1} = 810,58 \text{ K}$$

$$\gamma_p = \frac{2400 \text{ K}}{810,58 \text{ K}} = 2,96$$

$$\eta_D = 1 - \frac{1}{1,4} \cdot \frac{1}{12^{(1,4-1)}} \frac{2,96^{1,4} - 1}{2,96 - 1} = 0,52$$

$$\eta_D = \bar{\eta}_C = 1 - \frac{\bar{T}_L}{\bar{T}_H}$$

$$q_H = c_p(T_3 - T_2) = \bar{T}_H(s_3 - s_2)$$

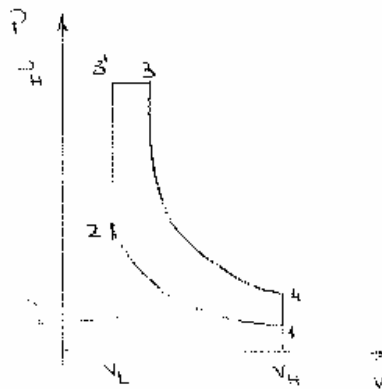
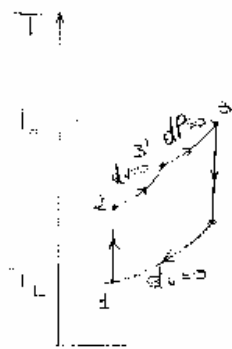
$$s_3 - s_2 = c_p \ln \frac{\bar{T}_3}{\bar{T}_2}$$

$$\bar{T}_H = \frac{\bar{T}_3 - \bar{T}_2}{\ln \bar{\tau}_p} = \frac{(2400 - 810,58) K}{\ln 2,96} = 1465 K$$

$$\bar{T}_L = \bar{T}_H(1 - \eta) = 1465 K (1 - 0,52) = 703,2 K$$

④

CICLO SARATHÉ



$$p = 12 = \frac{v_1}{v_2} = \frac{v_1}{v_{3'}} = \frac{v_H}{v_2} = \frac{v_H}{v_{3'}}$$

$$\bar{\tau}_p = \frac{T_3}{T_{3'}} = \bar{\tau}_v = \frac{T_{3'}}{T_2}$$

$$\eta = 1 - \frac{|q_L|}{q_H}$$

$$\eta = 1 - \frac{c_v(T_H - T_L)}{c_v(T_{3'} - T_2) + c_p(T_3 - T_{3'})} = 1 - \frac{T_H}{T_2} \frac{\left(\frac{T_H}{T_1} - 1\right)}{\left(\frac{T_{3'}}{T_2} - 1\right) + k \left(\frac{T_3}{T_2} - \frac{T_{3'}}{T_2}\right)}$$

$$\frac{T_H}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \frac{1}{p^{k-1}}$$

$$\frac{\bar{T}_3}{\bar{T}_2} = \frac{\bar{T}_3}{\bar{T}_3'} \cdot \frac{\bar{T}_3'}{\bar{T}_2} = \tau_p^2 \rightarrow \tau_p = \sqrt{\frac{\bar{T}_3}{\bar{T}_2}} = \sqrt{\frac{\bar{T}_3}{\bar{T}_1 \rho^{k-1}}} = 1,72$$

$$\frac{\bar{T}_4}{\bar{T}_1} = \frac{\bar{T}_4}{\bar{T}_3} \cdot \frac{\bar{T}_3}{\bar{T}_2} \cdot \frac{\bar{T}_2}{\bar{T}_1}$$

traj. 3 → 4

$$\bar{T}_4 v_4^{k-1} = \bar{T}_3 v_3^{k-1} \rightarrow \frac{\bar{T}_4}{\bar{T}_3} = \left(\frac{v_3}{v_4}\right)^{k-1} = \left(\frac{v_3}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_2} \cdot \frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_3'} \cdot \frac{v_2}{v_1}\right)^{k-1}$$

traj. 3' → 3

$$\frac{v}{T} = \text{cost}$$

$$\frac{v_3}{\bar{T}_3} = \frac{v_3'}{\bar{T}_3'} \rightarrow \frac{v_3}{v_3'} = \frac{\bar{T}_3}{\bar{T}_3'} = \tau_p$$

$$\frac{\bar{T}_4}{\bar{T}_1} = \tau_p^{k-1} \cdot \frac{1}{\rho^{k-1}} \cdot \tau_p^2 \cdot \rho^{k-1} = \tau_p^{k+1}$$

$$\eta = 1 - \frac{1}{\rho^{k-1}} \frac{(\tau_p^{k+1} - 1)}{(\tau_p - 1) + k(\tau_p^2 - \tau_p)} = 1 - \frac{1}{12^{1,4-1}} \frac{1,72^{1,4+1} - 1}{(1,72 - 1) + 1,4(1,72^2 - 1,72)} =$$

$$= 0,60$$

$$\eta_s = \eta_c = 1 - \frac{\bar{T}_L}{\bar{T}_H}$$

$$Q_{1H} = \bar{T}_H [(s_3 - s_{3'}) + (s_{3'} - s_2)] = c_v (\bar{T}_3' - \bar{T}_2) + c_p (\bar{T}_3 - \bar{T}_3')$$

$$s_3 - s_{3'} = c_p \ln \frac{\bar{T}_3}{\bar{T}_3'}$$

$$s_3 - s_2 = c_p \ln \frac{\bar{T}_3'}{\bar{T}_2} - R \ln \frac{\bar{p}_3'}{\bar{p}_2} = c_v \ln \frac{\bar{T}_3'}{\bar{T}_2}$$

$$\bar{T}_H = \frac{c_v (\bar{T}_3' - \bar{T}_2) + c_p (\bar{T}_3 - \bar{T}_3')}{\frac{c_p \ln \frac{\bar{T}_3'}{\bar{T}_2} + c_p \ln \frac{\bar{T}_3}{\bar{T}_3'}} = \frac{(\bar{T}_3' - \bar{T}_2) + k(\bar{T}_3 - \bar{T}_3')}{(\ln \tau_p)(k+1)}$$

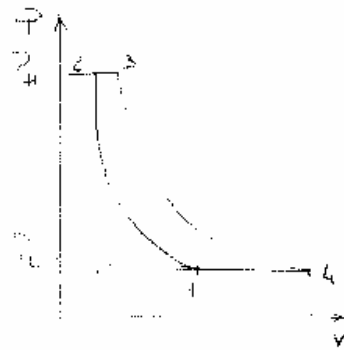
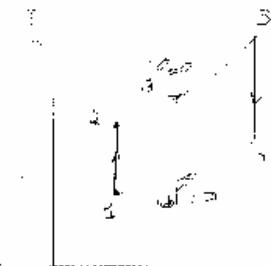
$$T_3' = \tau_p T_2 = \tau_p T_1 \rho^{k-1} = 1394 \text{ K}$$

$$\bar{T}_H = \frac{(1394 - 811) \text{ K} + 1,4 (2600 - 1394) \text{ K}}{(1,4 + 1) \ln 1,72} = 1530 \text{ K}$$

$$\bar{T}_L = \bar{T}_H (1 - \eta) = 1530 \text{ K} (1 - 0,60) = 612 \text{ K}$$

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$T_H$



$$\beta = \frac{P_2}{P_1} = 6 = \frac{P_3}{P_4} = \frac{P_3}{P_1} = \frac{P_3}{P_4}$$

$$\eta = 1 - \frac{|q_L|}{q_H}$$

$$q_H = c_p (T_3 - T_2)$$

$$|q_L| = c_p (T_4 - T_1)$$

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

trasf. 1-2

$$\frac{T_1}{P_1^\lambda} = \frac{T_2}{P_2^\lambda} \rightarrow \frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^\lambda = \frac{1}{\beta^\lambda}$$

trasf 3→4

$$\frac{T_3}{P_3^\lambda} = \frac{T_4}{P_4^\lambda} \rightarrow \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^\lambda = \beta^\lambda$$

$$\frac{T_3}{T_4} = \frac{T_2}{T_1} \rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\eta = 1 - \frac{1}{\beta^\lambda} = 1 - \frac{1}{6^{\frac{14-1}{14}}} = 0,40$$

$$\eta = \eta_c = 1 - \frac{T_L}{T_H}$$

$$q_H = \bar{T}_H(s_3 - s_2) = c_p(T_3 - T_2)$$

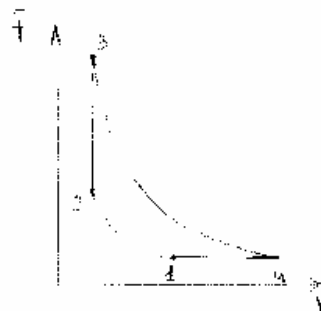
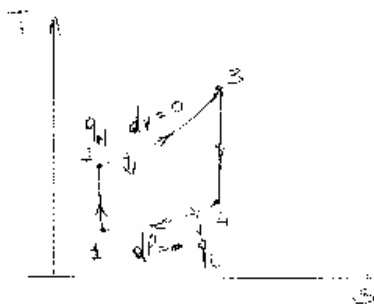
$$s_3 - s_2 = c_p \ln \frac{T_3}{T_2}$$

$$T_2 = T_1 \beta^\lambda = 501 \text{ K}$$

$$\bar{T}_H = \frac{T_3 - T_2}{\ln \frac{T_3}{T_2}} = \frac{(2400 - 501) \text{ K}}{\ln \frac{2400}{501}} = 1212 \text{ K}$$

$$\bar{T}_L = \bar{T}_H(1 - \eta) = 1212 \text{ K} (1 - 0,4) = 727 \text{ K}$$

④ CICLO HOLZWARTH



$$\beta = \frac{P_2}{P_1} = 6 = \frac{P_2}{P_4}$$

$$\tau_v = \frac{T_3}{T_2}$$

$$\eta = 1 - \frac{|q_L|}{q_H}$$

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

transf. 1→2

$$\frac{T_1}{P_1^\lambda} = \frac{T_2}{P_2^\lambda} \rightarrow \frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^\lambda = \frac{1}{\beta^\lambda}$$

$$\frac{T_4}{T_2} = \frac{T_4}{T_3} \frac{T_3}{T_2} = \frac{T_2}{T_1}$$

transf. 3→4

$$\frac{T_3}{P_3^\lambda} = \frac{T_4}{P_4^\lambda} \rightarrow \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^\lambda = \left(\frac{P_1}{P_3}\right)^\lambda = \left(\frac{P_1}{P_2} \cdot \frac{P_2}{P_3}\right)^\lambda$$

transf. 2→3  $v = \text{const.}$

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \rightarrow \frac{P_2}{P_3} = \frac{T_2}{T_3} = \frac{1}{\tau_v}$$

$$\frac{T_4}{T_1} = \frac{1}{\beta^\lambda} \cdot \frac{1}{\tau_v^\lambda} \cdot \tau_v \cdot \beta^\lambda = \tau_v^{\frac{1}{k}}$$

$$\eta = 1 - k \frac{1}{\beta^\lambda} \frac{(\tau_v^{\frac{1}{k}} - 1)}{(\tau_v - 1)}$$

$$T_2 = T_1 \beta^\lambda = 501 \text{ K}$$

$$\tau_v = \frac{T_3}{T_2} = \frac{2400}{501} = 4,79$$

$$\eta = 1 - 1,4 \frac{1}{6} \frac{4,79^{1,4} - 1}{4,79 - 1} = 0,54$$

$$\eta_H = \bar{\eta}_c = 1 - \frac{\bar{T}_L}{\bar{T}_H}$$

$$q_H = \bar{T}_H (s_3 - s_2) = c_v (T_3 - T_2)$$

$$s_3 - s_2 = c_p \ln \frac{T_3}{T_2} - R \ln \frac{P_3}{P_2} = c_v \ln \frac{T_3}{T_2}$$

$$\bar{T}_H = \frac{T_3 - T_2}{\ln \tau_v} = \frac{(2400 - 504) K}{\ln 4,79} = 1212 K$$

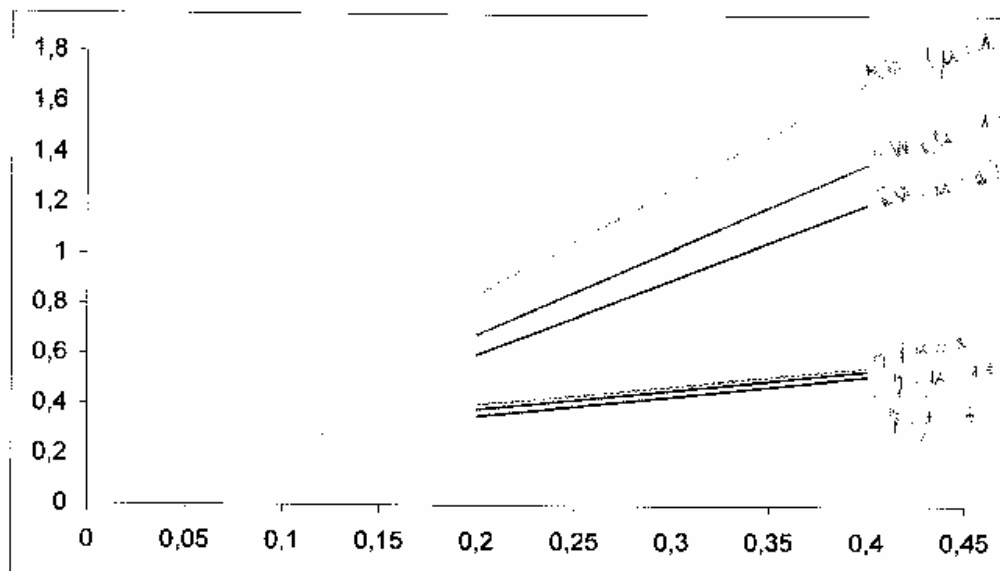
$$\bar{T}_L = \bar{T}_H (1 - \eta) = 1212 K (1 - 0,54) = 558 K$$

# APPLICAZIONE N° 20

scelgo  $\eta' = 0,25$

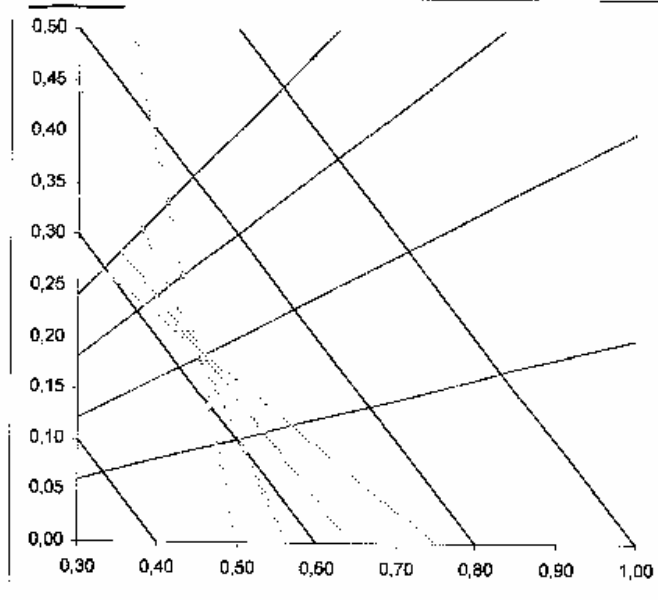
$$\eta = \frac{\eta'}{\mu} + \eta'' \left[ 1 - \frac{\eta'}{\mu} \right]$$

$$RW = \frac{\eta''}{\eta'} (\mu - \eta')$$



| $\eta'$ | RW           |              |              | $\eta$       |              |              |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|
|         | $\mu = 1,00$ | $\mu = 1,10$ | $\mu = 1,30$ | $\mu = 1,00$ | $\mu = 1,10$ | $\mu = 1,30$ |
| 0,00    | 0,00         | 0,00         | 0,00         | 0,25         | 0,23         | 0,19         |
| 0,05    | 0,15         | 0,17         | 0,21         | 0,29         | 0,27         | 0,23         |
| 0,10    | 0,30         | 0,34         | 0,42         | 0,33         | 0,30         | 0,27         |
| 0,15    | 0,45         | 0,51         | 0,63         | 0,36         | 0,34         | 0,31         |
| 0,20    | 0,60         | 0,68         | 0,84         | 0,40         | 0,38         | 0,35         |
| 0,25    | 0,75         | 0,85         | 1,05         | 0,44         | 0,42         | 0,39         |
| 0,30    | 0,90         | 1,02         | 1,26         | 0,48         | 0,46         | 0,43         |
| 0,35    | 1,05         | 1,19         | 1,47         | 0,51         | 0,50         | 0,48         |
| 0,40    | 1,20         | 1,36         | 1,68         | 0,55         | 0,54         | 0,52         |
| 0,45    | 1,35         | 1,53         | 1,89         | 0,59         | 0,58         | 0,56         |

# APPLICAZIONE N° 21



| Ut   | 1,00 | 0,80 | 0,60 | 0,40 | ← U |
|------|------|------|------|------|-----|
| 0,30 | 0,70 | 0,50 | 0,30 | 0,10 |     |
| 0,40 | 0,60 | 0,40 | 0,20 | 0,00 |     |
| 0,50 | 0,50 | 0,30 | 0,10 |      |     |
| 0,60 | 0,40 | 0,20 | 0,00 |      |     |
| 0,70 | 0,30 | 0,10 |      |      |     |
| 0,80 | 0,20 | 0,00 |      |      |     |
| 0,90 | 0,10 |      |      |      |     |
| 1,00 | 0,00 |      |      |      |     |

|      | 0,2  | 0,4  | 0,6  | 0,8  | ← Ume/Ut |
|------|------|------|------|------|----------|
| 0,30 | 0,06 | 0,12 | 0,18 | 0,24 |          |
| 0,40 | 0,08 | 0,16 | 0,24 | 0,32 |          |
| 0,50 | 0,10 | 0,20 | 0,30 | 0,40 |          |
| 0,60 | 0,12 | 0,24 | 0,36 | 0,48 |          |
| 0,70 | 0,14 | 0,28 | 0,42 | 0,56 |          |
| 0,80 | 0,16 | 0,32 | 0,48 | 0,64 |          |
| 0,90 | 0,18 | 0,36 | 0,54 | 0,72 |          |
| 1,00 | 0,20 | 0,40 | 0,60 | 0,80 |          |

|      | 0,2  | 0,40 | 0,60 | 0,80 | ← IR |
|------|------|------|------|------|------|
| 0,30 | 0,28 | 0,33 | 0,44 | 0,76 |      |
| 0,40 | 0,22 | 0,23 | 0,27 | 0,38 |      |
| 0,50 | 0,15 | 0,14 | 0,10 |      |      |
| 0,60 | 0,09 | 0,04 |      |      |      |
| 0,70 | 0,03 |      |      |      |      |

### APPLICAZIONE N° 22

aria :  $k = 1,4$

$$\rho = 1 \frac{\text{kg}}{\text{m}^3}$$

$$\dot{V} = 1000 \frac{\text{m}^3}{\text{h}}$$

$$P_i = 1 \text{ bar}$$

$$P_f = 16 \text{ bar}$$

$$T_i = 15^\circ\text{C}$$

$$|\dot{W}_d| = ?$$

$$\dot{V} = \frac{\dot{m}}{\rho} \rightarrow \dot{m} = \dot{V}\rho = 1000 \frac{\text{m}^3}{\text{h}} \cdot 1 \frac{\text{kg}}{\text{m}^3} = 1000 \frac{\text{kg}}{\text{h}} = \frac{1000 \text{ kg}}{3600 \text{ s}} = 0,36 \frac{\text{kg}}{\text{s}}$$

$$|\dot{W}_x| = \dot{m} |w_x|$$

$$\begin{aligned} |w_x| &= \int_{P_i}^{P_f} v dP = \int_{P_i}^{P_f} \left(\frac{P_i}{P}\right)^{\frac{1}{k}} v_i dP = v_i P_i^{\frac{1}{k}} \int_{P_i}^{P_f} \frac{1}{P^{\frac{1}{k}}} dP = \frac{v_i}{\lambda} P_i^{\frac{1}{k}} (P_f^\lambda - P_i^\lambda) = \\ &= \frac{v_i}{\lambda} P_i^{\frac{1}{k}} P_i^\lambda \left[ \left(\frac{P_f}{P_i}\right)^\lambda - 1 \right] = \frac{v_i P_i}{\lambda} [\beta^\lambda - 1] \end{aligned}$$

ma

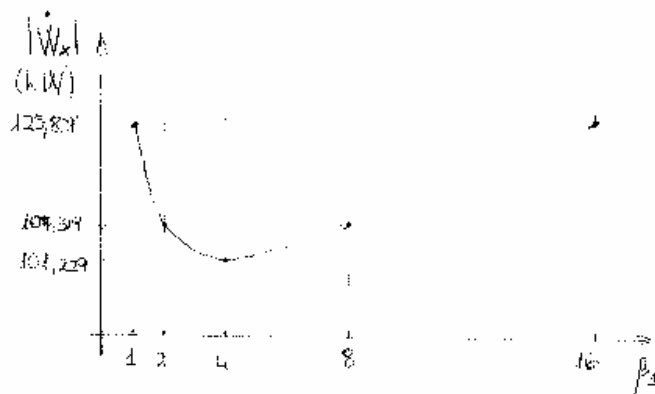
$$P_i v_i = R T_i$$

da cui

$$|w_x| = \frac{R T_i}{\lambda} (\beta^\lambda - 1) = c_p T_i (\beta^\lambda - 1)$$

$$|w_x|_{\text{tot}} = c_p T_i \sum_{j=1}^N (\beta_j^\lambda - 1)$$

| $\beta_1$ | $\beta_2$ | $ w_\lambda  \left( \frac{J}{kg} \right)$ | $ \dot{W}_\lambda  = m w_\lambda  \quad (W)$ |
|-----------|-----------|-------------------------------------------|----------------------------------------------|
| 1         | 16        | 349521                                    | 125827                                       |
| 2         | 8         | 298108                                    | 107319                                       |
| 4         | 4         | 281192                                    | 101229                                       |
| 8         | 2         | 298108                                    | 107319                                       |
| 16        | 1         | 349521                                    | 125827                                       |



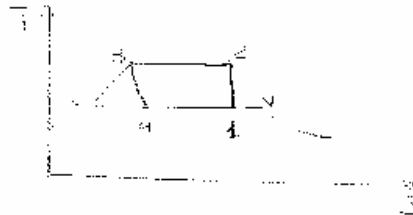
La condizione ottimale si ha quando  $\beta_1 = \beta_2 = 4$ .

### APPLICAZIONE N°23

$t_L = -15^\circ\text{C}$   $\rightarrow$  dalle tabelle  $p = 2,362 \text{ bar}$   
 $t_H = 30^\circ\text{C}$   $\rightarrow p = 11,669 \text{ bar}$   
 $m = 1 \text{ kg}$

$\text{COP} = ?$

$q_L = ?$



$$q_L = h_1 - h_4 = h_1 - h_3$$

per ricavare il titolo del punto 4 uso la regola della leva

$$S_1 = S_L + (S_V - S_L) x_1$$

$$S_L = 1,64667 \frac{\text{kJ}}{\text{kg K}}$$

$$S_V = 6,72727 \frac{\text{kJ}}{\text{kg K}}$$

$$S_1 = S_2 = 6,16259 \frac{\text{kJ}}{\text{kg K}}$$

$$x_1 = \frac{S_2 - S_L}{S_V - S_L} = \frac{6,16259 - 1,64667}{6,72727 - 1,64667} = 0,89$$

$$h_1 = h_L + (h_V - h_L) x_1$$

$$h_L = 355,69 \frac{\text{kJ}}{\text{kg}}$$

$$h_V = 1667,24 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = 355,69 \frac{\text{kJ}}{\text{kg}} + (1667,24 - 355,69) \frac{\text{kJ}}{\text{kg}} \cdot 0,89 = 1522,97 \frac{\text{kJ}}{\text{kg}}$$

$$h_4 = h_3 = 562,75 \frac{\text{kJ}}{\text{kg}}$$

$$q_L = h_1 - h_3 = (1522,97 - 562,75) \frac{\text{kJ}}{\text{kg}} = 960,22 \frac{\text{kJ}}{\text{kg}}$$

$$|w_x| = |w_{x,c}| = h_2 - h_1$$

$$h_2 = 1709,33 \frac{\text{kJ}}{\text{kg}}$$

$$|w_x| = (1709,33 - 1522,97) \frac{\text{kJ}}{\text{kg}} = 186,36 \frac{\text{kJ}}{\text{kg}}$$

$$\text{COP} = \varepsilon_F = \frac{q_L}{|w_x|} = 5,15$$

$$\varepsilon_F^{10} = \frac{T_L}{T_H - T_L} = \frac{258 \text{ K}}{(303 - 258) \text{ K}} = 5,73$$

### APPLICAZIONE N° 24

$$\dot{Q}_H = 50 \text{ kW}$$

$$t = 20^\circ\text{C}$$

$$t_0 = 2^\circ\text{C}$$

$$\Delta T = 20^\circ\text{C}$$

$$t_H = t + \Delta T = 40^\circ\text{C} \longrightarrow P = 15,3310 \text{ bar}$$

$$t_0 = t_L + \Delta T \longrightarrow t_L = -18^\circ\text{C} \longrightarrow P = 2,64181 \text{ bar}$$

$$\dot{W}_x = \dot{m} (h_1 - h_2)$$

$$\dot{m} = \frac{\dot{Q}_H}{q_H}$$

$$\Rightarrow \dot{W}_x = \dot{Q}_H \frac{(h_1 - h_2)}{h_3 - h_2}$$

$$h_1 = 398,312 \frac{\text{kJ}}{\text{kg}}$$

$$h_3 = 249,684 \frac{\text{kJ}}{\text{kg}}$$

$$s_2 = s_1 = 1,78065$$

$$h_2 \approx 443,50 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{W}_x = 50 \text{ kW} \frac{(398,312 - 443,50)}{249,684 - 443,50} = 11,66 \text{ kW}$$

$$\varepsilon_P = \frac{\dot{Q}_H}{\dot{W}_x} = \frac{50 \text{ kW}}{11,66 \text{ kW}} = 4,29$$

$$\dot{W}'_x = 0,96 \dot{W}_x = 0,96 \cdot 11,66 \text{ kW} = 11,19 \text{ kW}$$

$$\dot{W}_x' = \dot{m}'(h_1 - h_2) = \frac{\dot{Q}_H (h_1 - h_2)}{h_{3'} - h_2}$$

$$h_{3'} = \frac{\dot{Q}_H (h_1 - h_2)}{\dot{W}_x'} + h_2 = \frac{50 \text{ kW}}{11,19 \text{ kW}} (398,312 - 443,50) \frac{\text{kJ}}{\text{kg}} + 443,50 \frac{\text{kJ}}{\text{kg}} =$$
$$= 241,59 \frac{\text{kJ}}{\text{kg}}$$

$$t \sim 34^\circ\text{C} \rightarrow \Delta T \sim 14^\circ\text{C} < 20^\circ\text{C}$$

In teoria è possibile, nella pratica il problema è il  $\Delta T$ .

$$E_p = \frac{50 \text{ kW}}{11,19 \text{ kW}} = 4,47$$

### APPLICAZIONE N° 25

$$H = 795 \text{ m}$$

$$Q = 9,2 \frac{\text{m}^3}{\text{s}}$$

$$PP = 7$$

$$f = 50 \text{ Hz}$$

$$\eta_{\text{rot}} = 0,90$$

$$\psi = 0,98$$

$$n_b = ?$$

$$N = \frac{60f}{PP} = \frac{60 \cdot 50}{7} \frac{\text{giri}}{\text{min}} = 428,57 \frac{\text{giri}}{\text{min}}$$

$$\dot{W} = \eta_{\text{rot}} \rho Q g H = 0,9 \cdot 1000 \frac{\text{kg}}{\text{m}^3} \cdot 9,2 \frac{\text{m}^3}{\text{s}} \cdot 9,81 \frac{\text{m}}{\text{s}^2} \cdot 795 \text{ m} = 64575,31 \text{ kW} = 86530 \text{ CV}$$

$$n_b = \frac{N \dot{W}^{\frac{1}{2}}}{H^{\frac{5}{4}}} = \frac{428,57 \cdot \sqrt{86530}}{795^{\frac{5}{4}}} = 29,86$$

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$$C_1 = \psi \sqrt{2gH} = 0,98 \sqrt{2 \cdot 9,81 \frac{\text{m}}{\text{s}^2} \cdot 795 \text{ m}} = 122 \frac{\text{m}}{\text{s}}$$

$$U = \frac{C_1}{2} = 61 \frac{\text{m}}{\text{s}}$$

$$U = \frac{D}{2} \omega = \frac{D}{2} \frac{2\pi N}{60} \rightarrow D = \frac{60}{\pi} \frac{U}{N} = \frac{60}{\pi} \frac{61}{428,57} = 2,72 \text{ m}$$

### APPLICAZIONE N° 26

$$t = 60^\circ\text{C} \rightarrow p_s = 0,19920 \text{ bar} \approx 19920 \text{ Pa}$$

$$\rho = 983 \frac{\text{kg}}{\text{m}^3} \rightarrow \gamma = \rho g = 983 \frac{\text{kg}}{\text{m}^3} \cdot 9,81 \frac{\text{m}}{\text{s}^2} = 9643,23 \frac{\text{N}}{\text{m}^3}$$

$$h_p = 1,5 \text{ m}$$

$$\text{NPSH}_R = 3 \text{ m}$$

$$h_a = ?$$

$$\frac{p_s}{\gamma} = \frac{19920 \text{ Pa}}{9643,23 \frac{\text{N}}{\text{m}^3}} = 2,07 \text{ m}$$

$$\frac{p_{\text{tot}}}{\gamma} = \frac{101325 \text{ Pa}}{9643,23 \frac{\text{N}}{\text{m}^3}} = 10,50 \text{ m}$$

$$\frac{p_{\text{tot}}}{\gamma} = \text{NPSH}_R + h_p + \frac{p_s}{\gamma} + h_a$$

$$\Rightarrow h_a = \frac{p_{\text{tot}}}{\gamma} - \text{NPSH}_R - h_p - \frac{p_s}{\gamma} = (10,50 - 3 - 1,5 - 2,07) \text{ m} = 3,93 \text{ m}$$

### APPLICAZIONE N° 27

$$t_{max} = ?$$

$$|h_a| = 80 \text{ cm}$$

$$h_p = 2,5 \text{ m}$$

$$NPSH_R = 3,8 \text{ m}$$

$$\rho = 1000 \frac{\text{kg}}{\text{m}^3} \rightarrow \gamma = \rho g = 1000 \frac{\text{kg}}{\text{m}^3} \cdot 9,81 \frac{\text{m}}{\text{s}^2} = 9810 \frac{\text{N}}{\text{m}^3}$$

$$\frac{P_0}{\gamma} + |h_a| = NPSH_R + h_p + \frac{P_s}{\gamma}$$

$$\frac{P_0}{\gamma} = \frac{101325 \text{ Pa}}{9810 \frac{\text{N}}{\text{m}^3}} = 10,33 \text{ m}$$

$$\frac{P_s}{\gamma} = \frac{P_0}{\gamma} + |h_a| - NPSH_R - h_p = (10,33 + 0,80 - 3,8 - 2,5) \text{ m} = 4,83 \text{ m}$$

$$P_s = \gamma \cdot 4,83 \text{ m} \cdot 9810 \frac{\text{N}}{\text{m}^3} = 47382,3 \text{ Pa}$$

$$\Rightarrow t_s = 80^\circ\text{C}$$