lezione 17-18

Schiere supersoniche

$M_1 < 1$
$M_2 < 1$

compressore subsonico

$M_1 > 1$
$M_2 < 1$

compressore transonico

$M_{1a} < 1$

a) Regime innescato
b) Regime non innescato

$M_{1a} > 1$

regime saturo

Schiere supersoniche

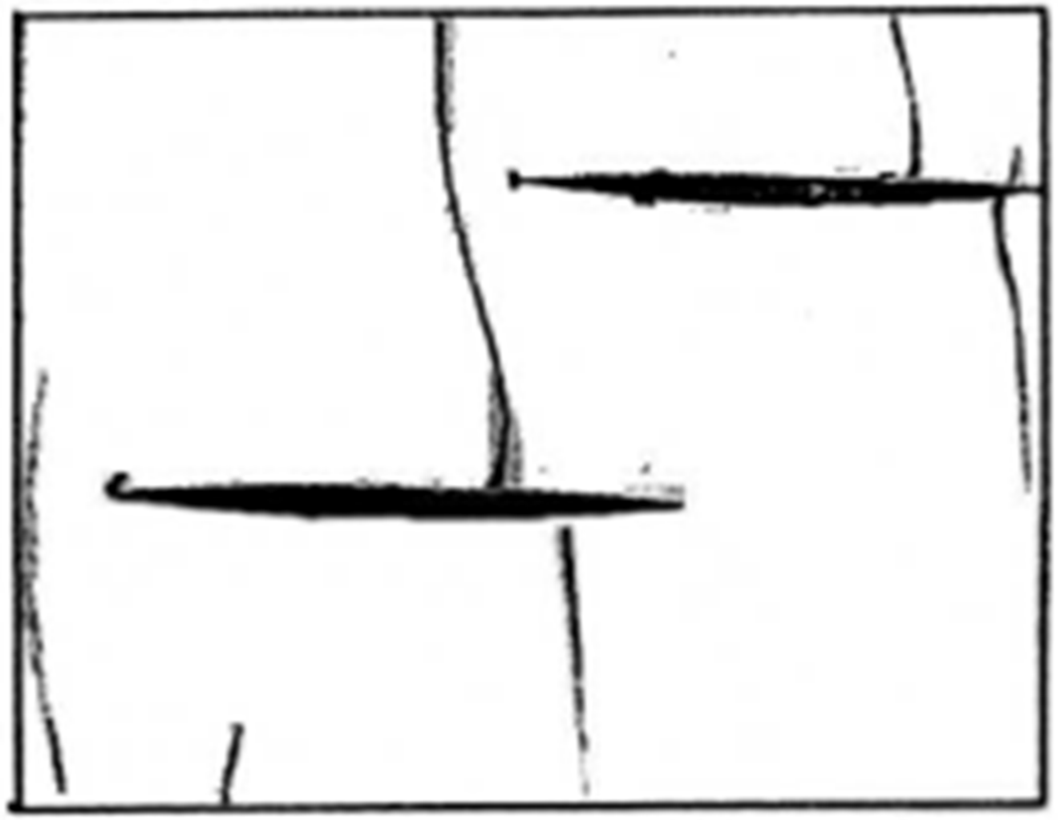
$$M_1 < 1$$
$$M_2 > 1$$

Flusso accelerato (non rilevante per i compressori)

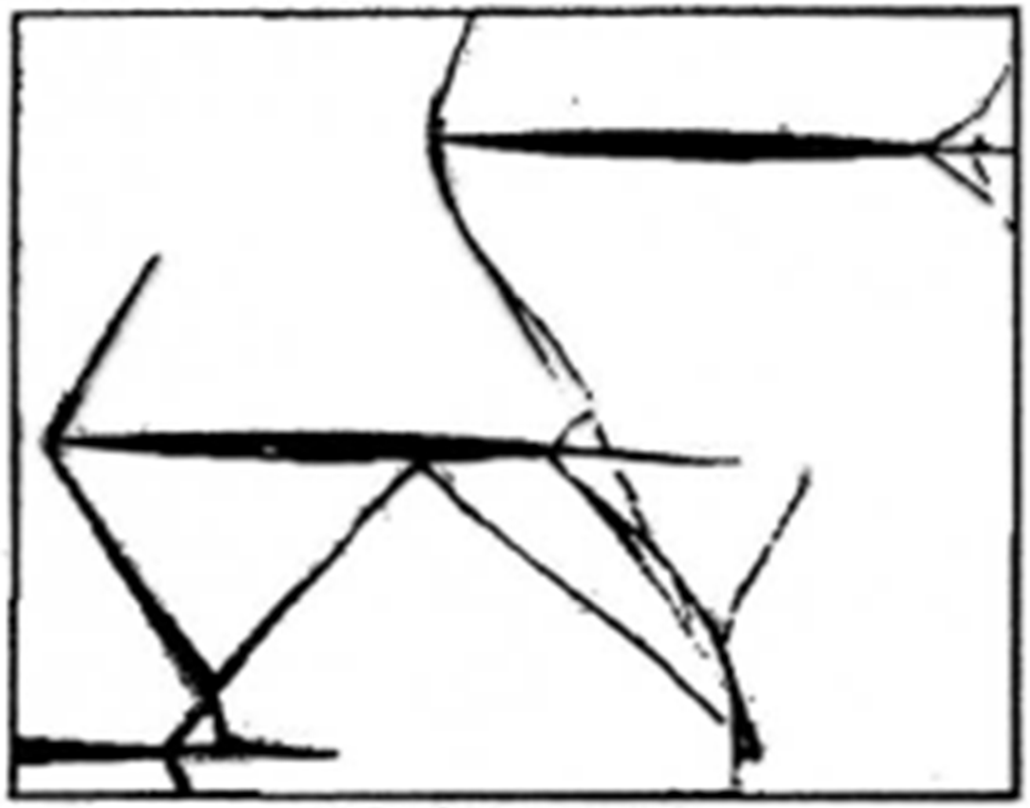
$$M_1 > 1$$
$$M_2 > 1$$

Flusso completamente supersonico

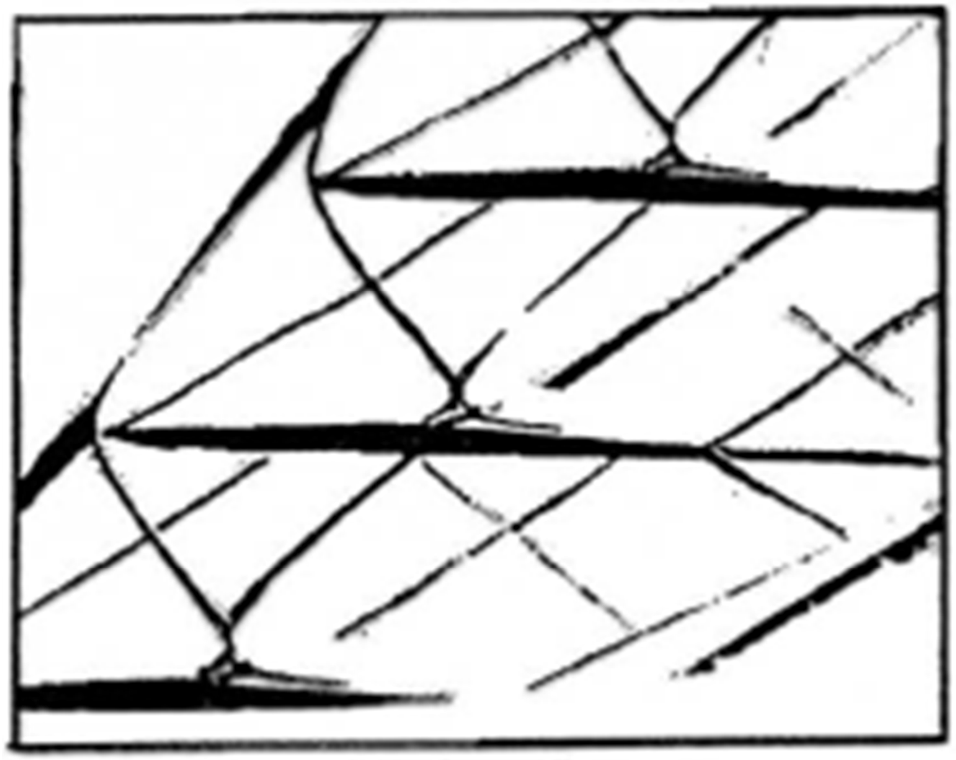
Schiere supersoniche



a) Regime non innescato

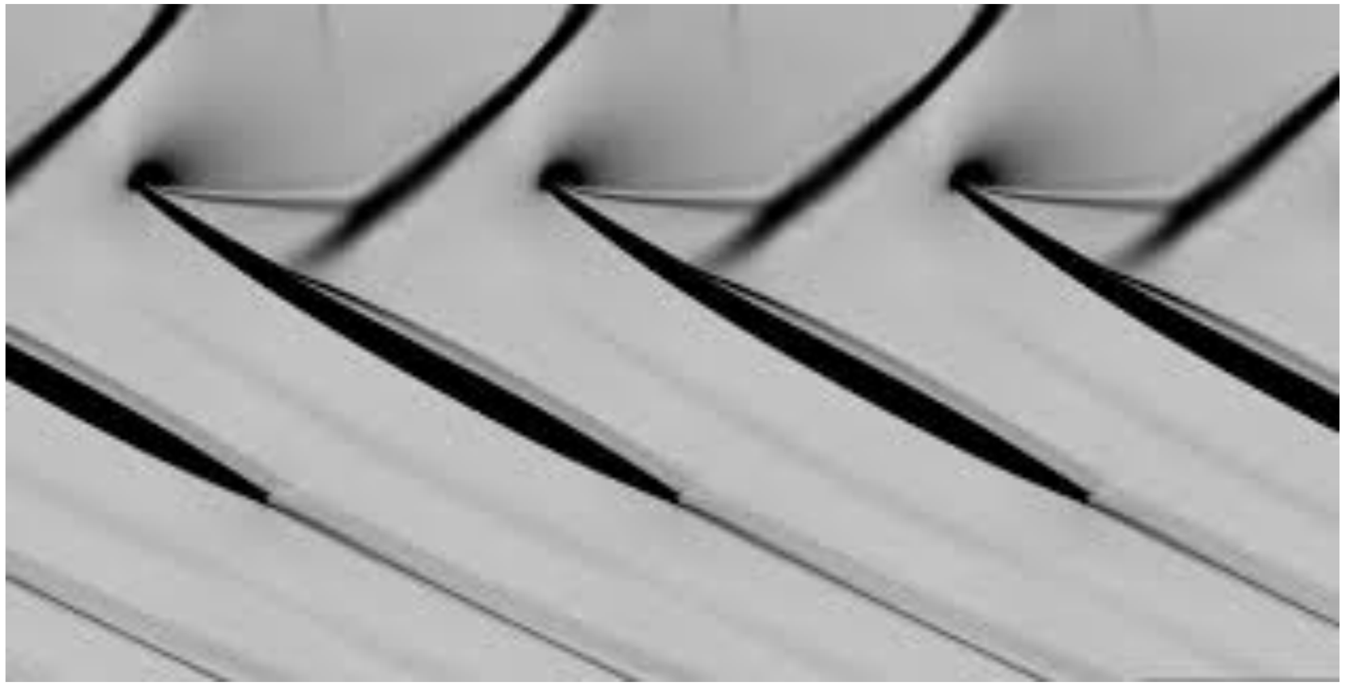


b) Regime innescato



c) Regime saturato

regime non innescato



regime innescato

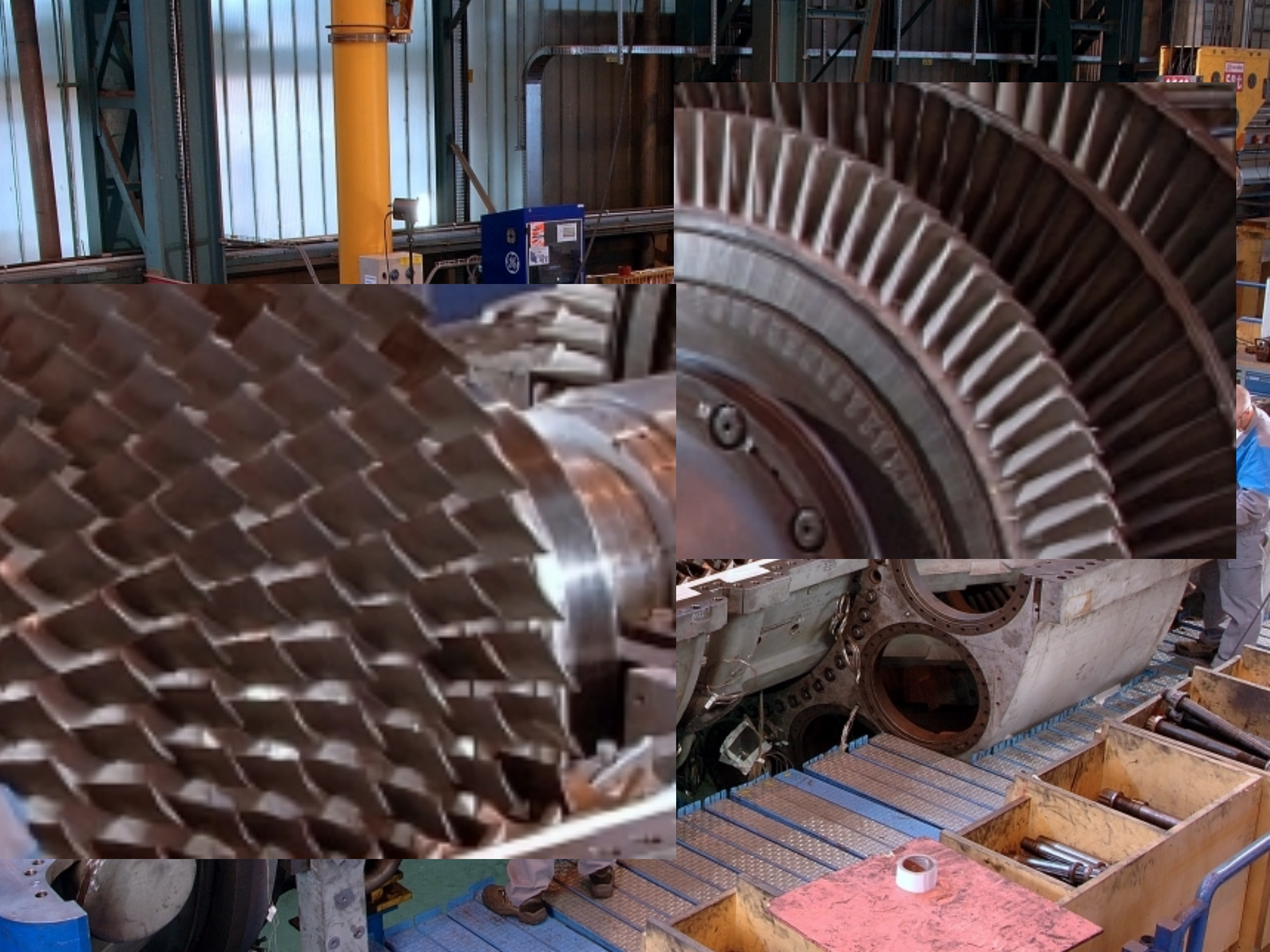
Turbine a flusso assiale e misto

1) h0 e T0 decrescono molto rapidamente nello stadio, $\rho \neq \mathrm{cost}$

2) T elevata, > 900°C

3) Deflessione maggiore rispetto ai compressori: Turbina 50°-180°, compressore 20°-35°

4) profili diversi dai compressori, variazione di sezione importante



Turbine a flusso assiale e misto (dal corso di macchine)

- Stadi ad azione $R = 0$

$$\begin{cases} \text{De Laval} & z_v = 1 & \text{(primo stadio)} \\ \text{Curtis} & z_v = 2 \div 3 & \\ \text{Reteau} & z_v = 1 & \text{(stadio intermedio)} \end{cases}$$

- $R = 0{,}5$

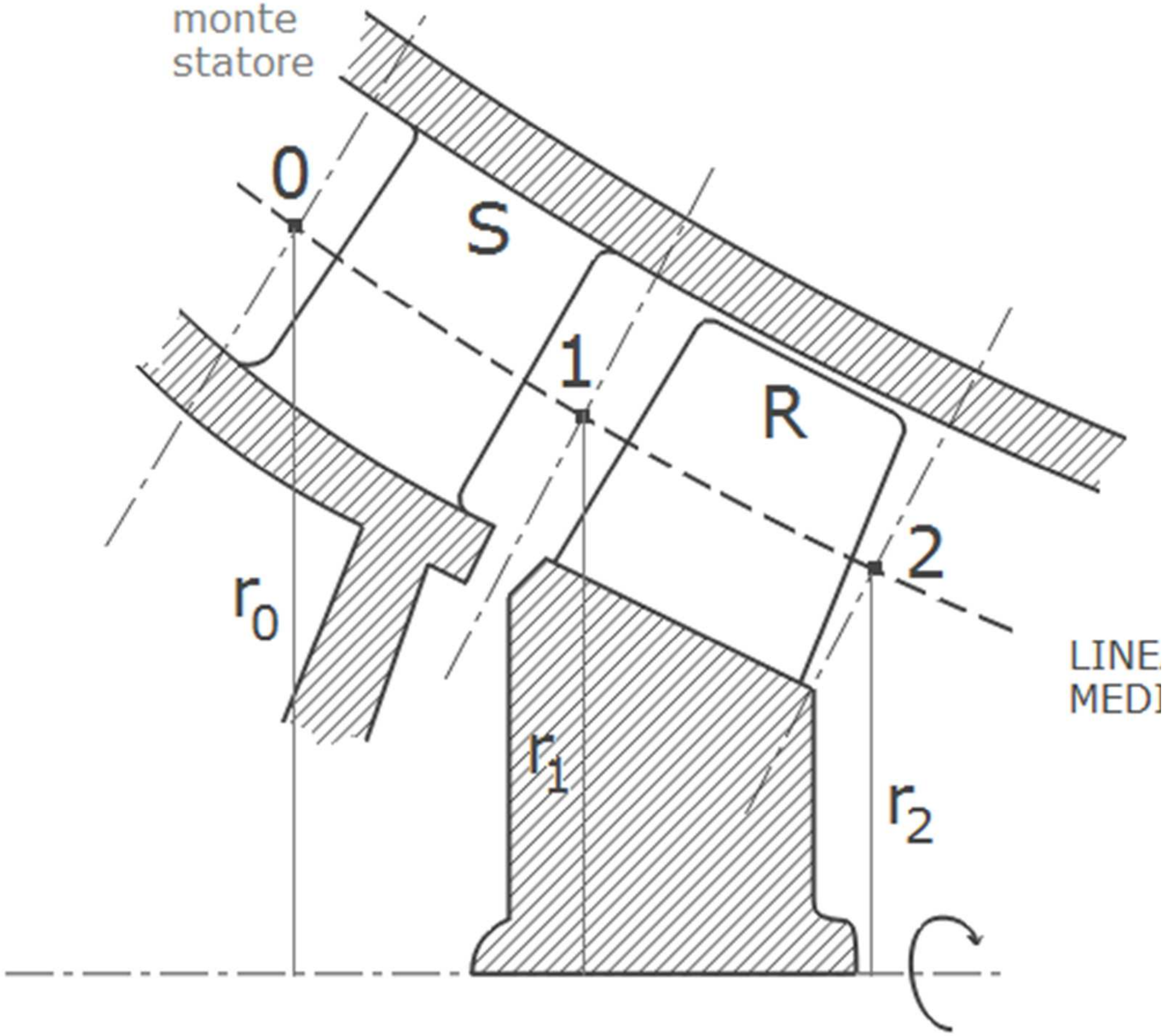
$$\{\text{Parsons}$$

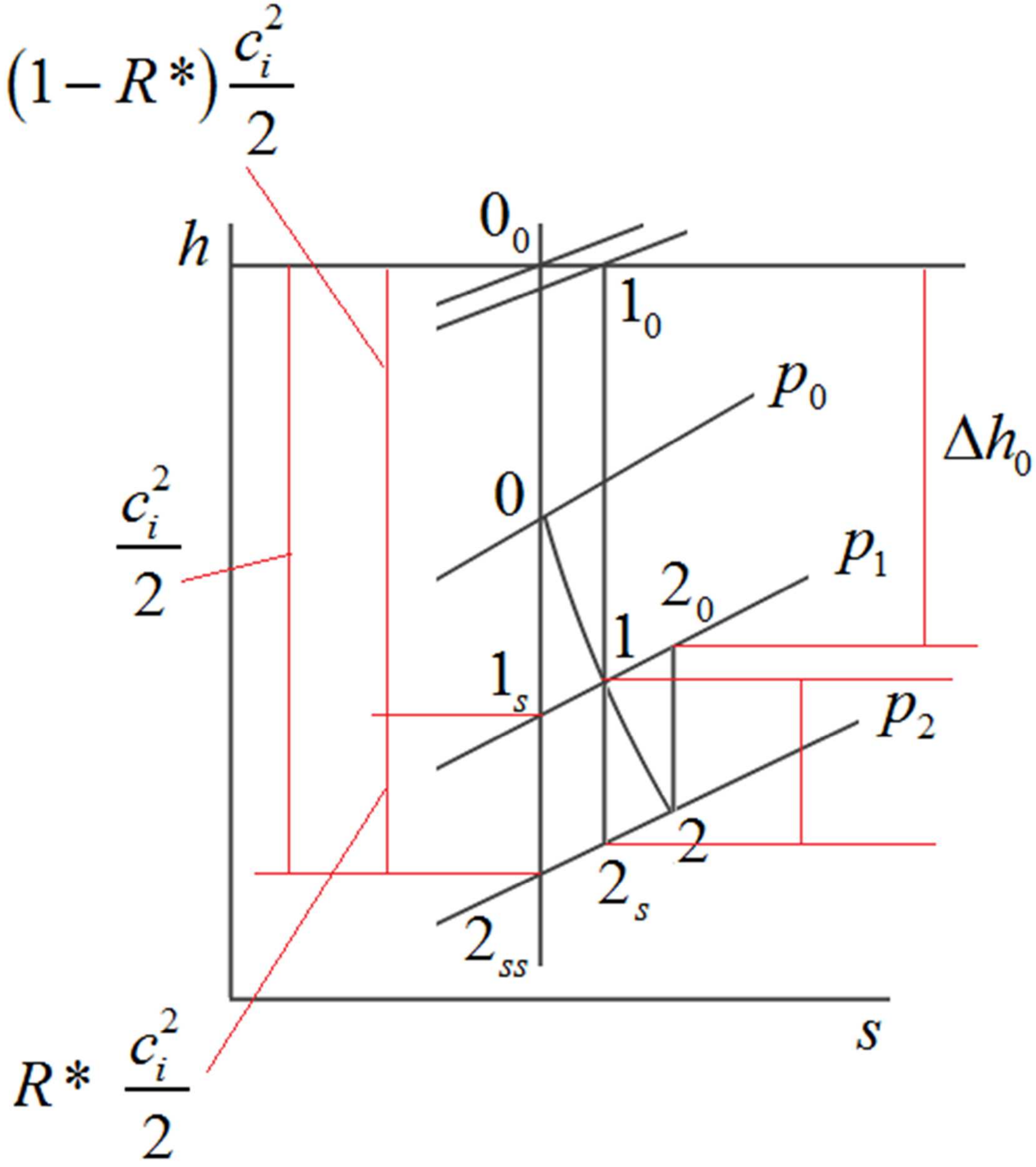
$$\left(\frac{u}{c_1}\right)_{opt} = \frac{sen\alpha_1}{2z_v} \qquad \text{per } R = 0$$

$$\left(\frac{u}{c_1}\right)_{opt} = sen\alpha_1 \qquad \text{per } R = 0{,}5$$

α_1 piccolo → $sen\alpha_1 = \alpha_1$

Turbine a flusso assiale e misto





Turbine a flusso assiale e misto

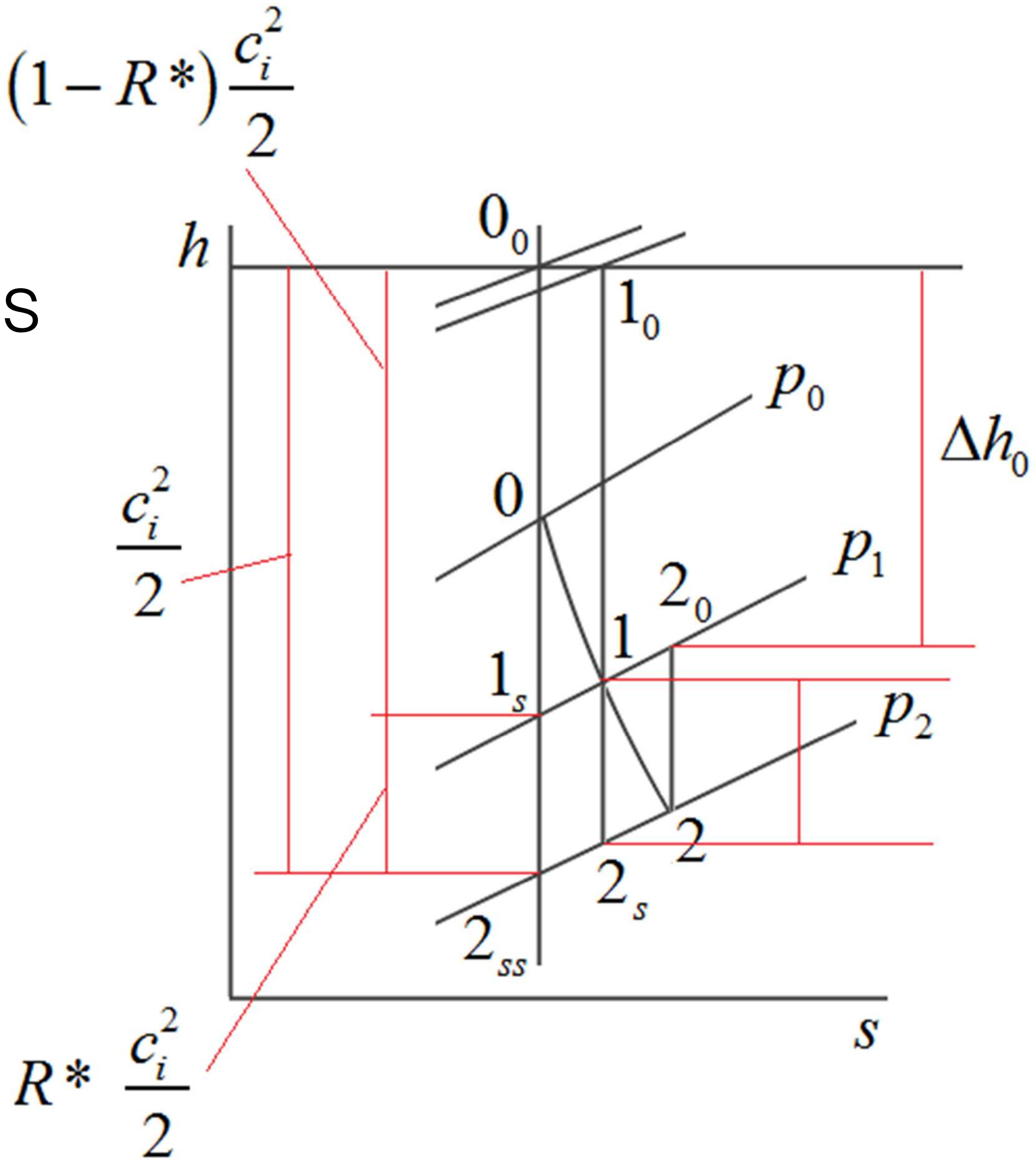
$$\left(1-R^*\right)\cdot\frac{c_i^2}{2}$$

Salto entalpico con espansione isoentropica

$$\left(1+f\right)R^*\cdot\frac{c_i^2}{2}$$

Salto fra 1 e 2s

f fattore di recupero



Turbine a flusso assiale e misto

$$\eta = \frac{h_{0_0} - h_{0_2}}{h_{0_0} - h_{2_{ss}} - \phi_E \frac{c_2^2}{2}} = \frac{\Delta h_0}{\Delta h_{is_{ts}} - \phi_E \frac{c_2^2}{2}}$$

$$\phi_E = 1 \quad \Rightarrow \quad \eta = \eta_{tt}$$

$$\phi_E = 0 \quad \Rightarrow \quad \eta = \eta_{ts}$$

definizioni:

$$\psi = \frac{h_{0_0} - h_{2ss}}{\frac{u_1^2}{2}} = \frac{c_i^2}{u_1^2} = \frac{\Delta h_{is_{ts}}}{\frac{u_1^2}{2}}$$

$$\phi_1 = \frac{c_{m1}}{u_1}$$ Coeff. di portata

$$R^* = \frac{h_{1s} - h_{2ss}}{h_{0_0} - h_{2ss}} = \frac{\Delta h_{Ris}}{\Delta h_{ists}}$$ Grado di reazione

Turbine a flusso assiale e misto

definizioni:

$$\psi = \frac{h_{0_0} - h_{2ss}}{\frac{u_1^2}{2}} = \frac{c_i^2}{u_1^2} = \frac{\Delta h_{is_{ts}}}{\frac{u_1^2}{2}}$$

Coeff. di lavoro specifico ideale

$$\frac{c_i^2}{2} = h_{0_0} - h_{2_{ss}}$$

energia cinetica ideale

$$k_{is} = \frac{u_1}{c_i} = \frac{1}{\sqrt{\psi}}$$

Coeff. di velocità periferica

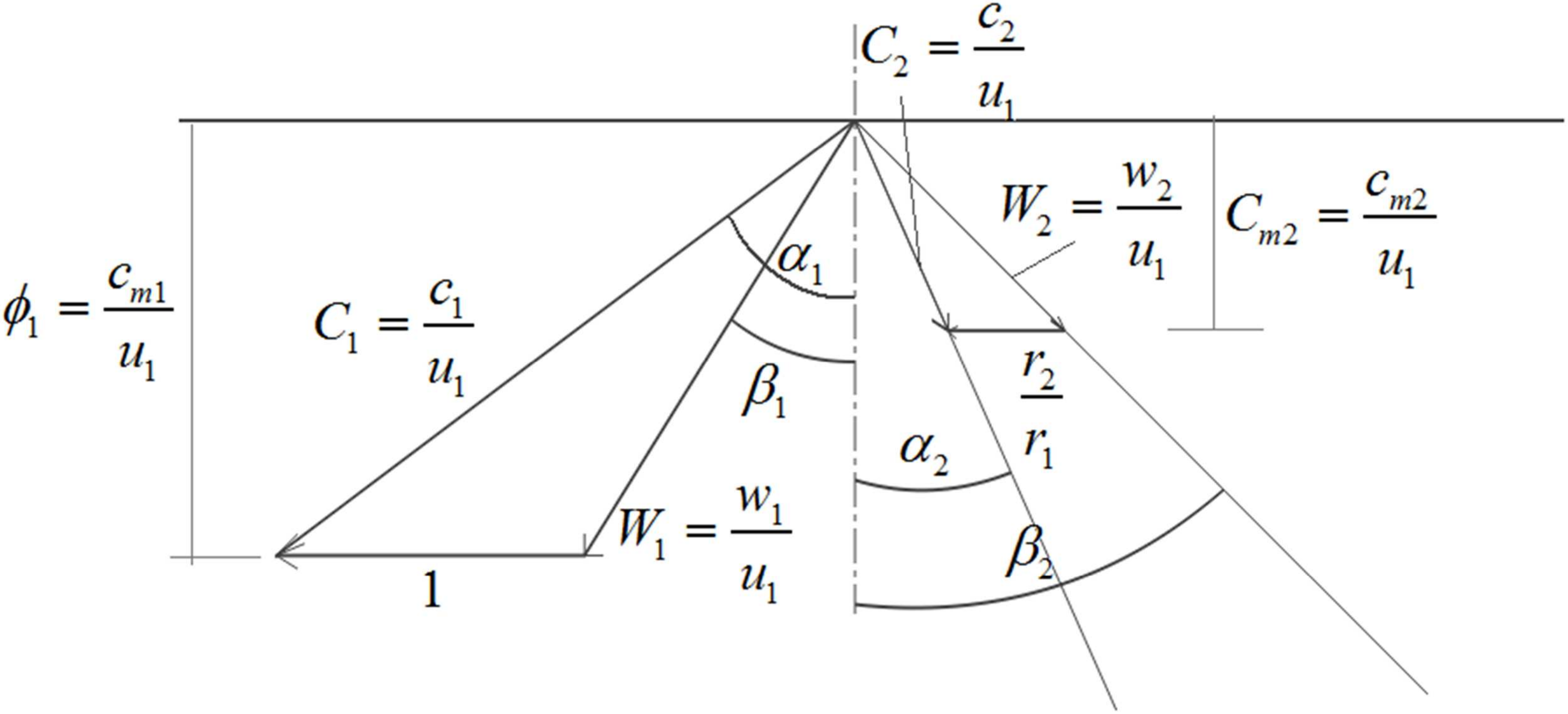
$$\lambda = \frac{h_{0_0} - h_{2_0}}{\frac{u_1^2}{2}} = \frac{\Delta h_0}{\frac{u_1^2}{2}}$$

Coeff. di lavoro specifico reale

Turbine a flusso assiale e misto

$\dfrac{c_{m2}}{c_{m1}}$ rapp. fra le velocità meridiane

$\dfrac{r_2}{r_1}$ rapporto fra i raggi, =1 macchina assiale



Turbine a flusso assiale e misto

$$\eta = \frac{\Delta h_0}{\Delta h_{is_{ts}} - \phi_E \frac{c_2^2}{2}} \cdot \frac{\frac{1}{\left(u_1^2/2\right)}}{\frac{1}{\left(u_1^2/2\right)}} = \frac{\lambda}{\psi - \phi_E \left(C_2^2\right)}$$

$$\lambda = \frac{\Delta h_0}{\frac{u_1^2}{2}} = \frac{2\left(u_1 c_{u1} - u_2 c_{u2}\right)}{u_1^2} = 2\left(C_{u1} - \frac{r_2}{r_1} C_{u2}\right)$$

Turbine a flusso assiale e misto

C1 Velocità assoluta adimensionalizzata

$$\frac{c_1^2}{2} = (1 - R^*)\frac{c_i^2}{2} \cdot \eta_S \quad \rightarrow \quad c_1 = \sqrt{\eta_S (1 - R^*)} \cdot c_i$$

$$C_1 = \frac{c_1}{u_1} = \sqrt{\eta_S (1 - R^*)} \cdot \frac{c_i}{u_1} \qquad \frac{c_i}{u_1} = \frac{1}{k_{is}}$$

$$\boxed{C_1 = \frac{\sqrt{\eta_S}}{k_{is}} \sqrt{1 - R^*}}$$

Turbine a flusso assiale e misto

W1 Velocità relativa adimensionalizzata

$$W_1^{\,2} = C_1^2 + 1^2 - 2 \cdot 1 \cdot C_1 \cos\left(90° - \alpha_1\right)$$

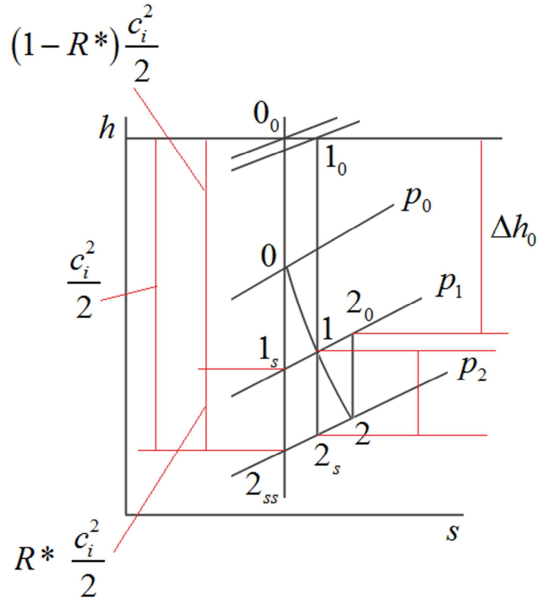
$$\boxed{W_1 = \sqrt{1 + \frac{\eta_S}{k_{is}^2}\left(1 - R*\right) - 2\frac{\sqrt{\eta_S}}{k_{is}}\sqrt{1 - R*} \cdot sen\alpha_1}}$$

Turbine a flusso assiale e misto

W2 Velocità relativa adimensionalizzata

$$h_2 - h_1 = \frac{u_2^2 - u_1^2}{2} - \frac{w_2^2 - w_1^2}{2}$$

rotalpia



$$h_1 - h_2 = \frac{c_i^2}{2} \cdot R^*\left(1+f\right)\eta_R$$

$$\frac{w_2^2 - w_1^2}{2} - \frac{u_2^2 - u_1^2}{2} = \frac{c_i^2}{2} \cdot R^*\left(1+f\right)\eta_R \qquad \cdot\!/\ \frac{1}{u_1^2}$$

$$\boxed{W_2 = \sqrt{\frac{\eta_R\left(1+f\right)R^*}{k_{is}^2} + \frac{\eta_S}{k_{is}^2}\left(1+R^*\right) - \frac{2\sqrt{\eta_S}}{k_{is}}\sqrt{1-R^*}\,sen\alpha_1 + \left(\frac{r_2}{r_1}\right)^2}}$$

Turbine a flusso assiale e misto

Cm2 Velocità meridiana assoluta adimensionalizzata

$$c_{m2} = c_{m1} \cdot \frac{c_{m2}}{c_{m1}} = c_1 \cos\alpha_1 \cdot \frac{c_{m2}}{c_{m1}}$$

$$C_{m2} = C_1 \cos\alpha_1 \cdot \frac{c_{m2}}{c_{m1}}$$

$$\boxed{C_{m2} = \frac{c_{m2}}{c_{m1}} \frac{\sqrt{\eta_S}}{k_{is}} \sqrt{1 - R^*} \cos\alpha_1}$$

Turbine a flusso assiale e misto

$$\eta = f\left(\psi, \phi_R, R^*, k_{is}, f, \frac{c_{m2}}{c_{m1}}, \frac{r_2}{r_1}, \alpha_1, \eta_S, \eta_R\right)$$

$\psi, \phi_R, R^*, k_{is}$: parametri funzionali

f : unica grandezza che dipende dalla natura del fluido

$\frac{c_{m2}}{c_{m1}}, \frac{r_2}{r_1}, \alpha_1$: parametri di progetto

η_S, η_R : parametri della schiera rotorica e statorica

Turbine a flusso assiale e misto

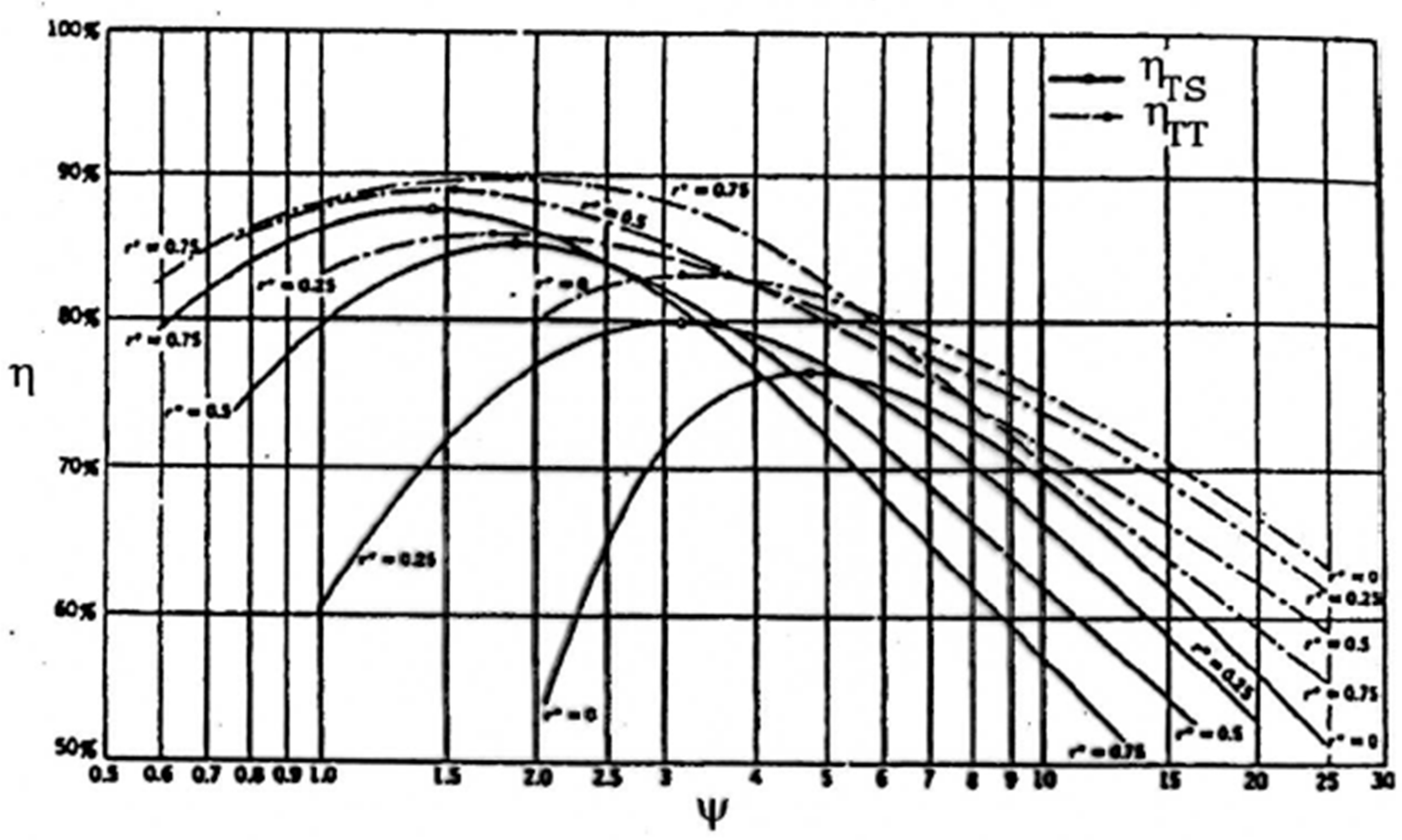
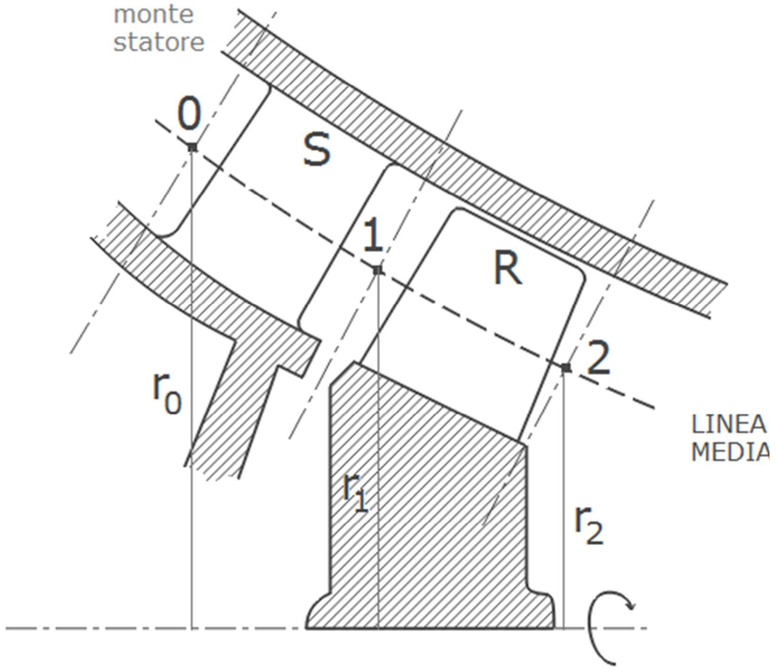


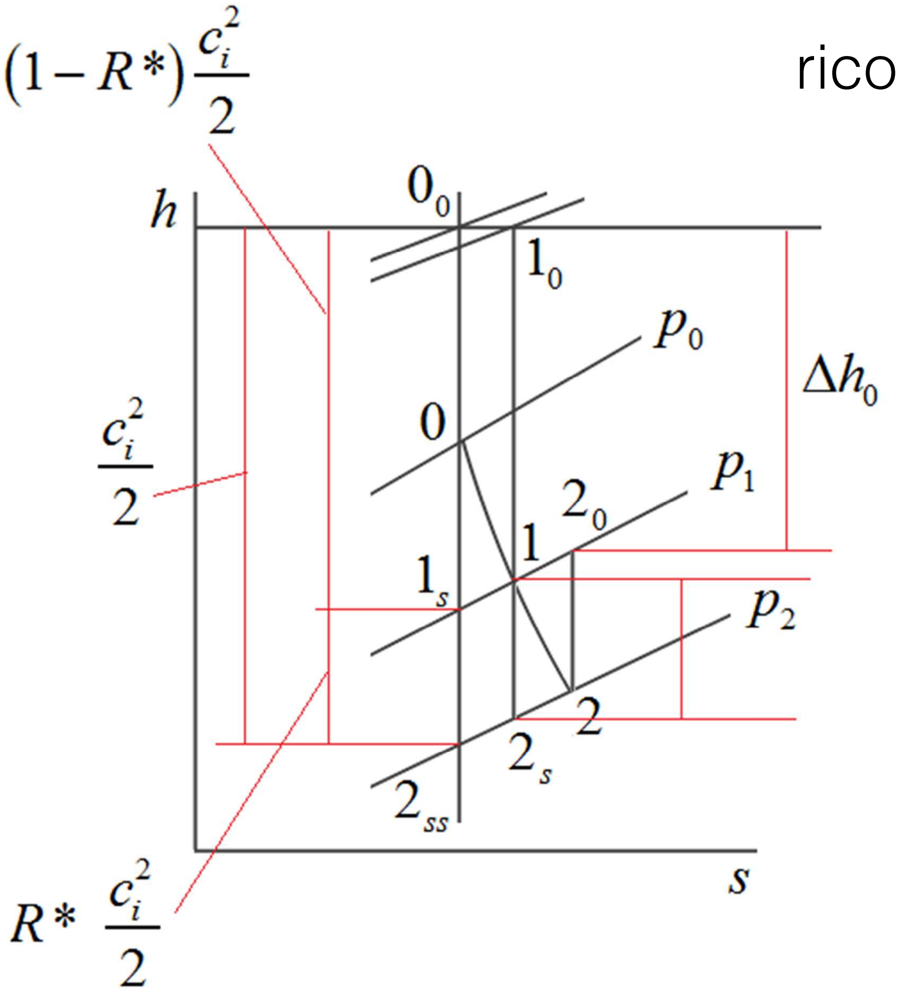
Figura 9.9: *Rendimenti total/static e total/total di un generico stadio di turbina in funzione del lavoro adimensionale per diversi gradi di reazione.*

Calcolo delle proprietà termodinamiche nell'attraversamento della turbina



$$M_u = \frac{u_1}{a_{0_0}}$$ def. Mach periferico

$$a_{0_0} = \sqrt{kRT_{0_0}} = \sqrt{\frac{c_p}{c_v}\left(c_p - c_v\right)T_{0_0}} = \sqrt{h_{0_0}\left(k-1\right)}$$

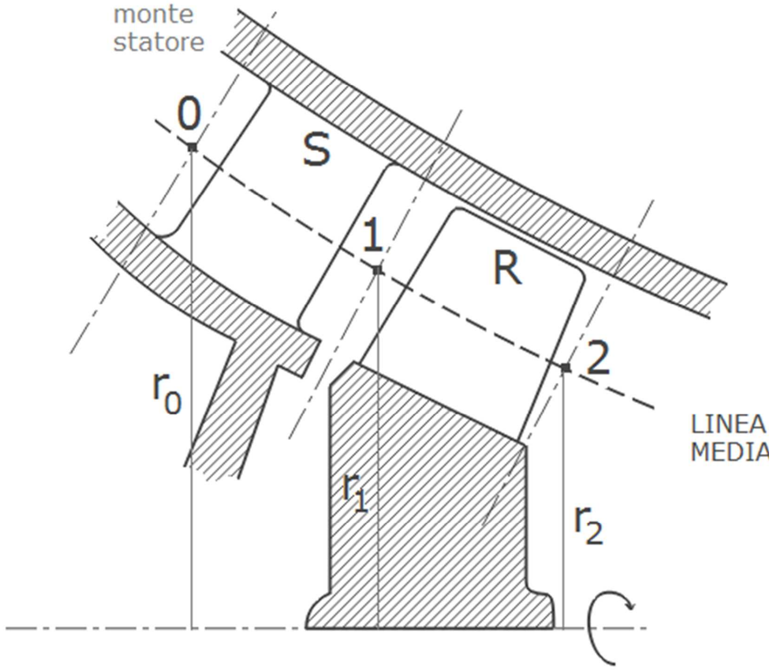


ricordiamo:

$$\psi = \frac{h_{0_0} - h_{2ss}}{\frac{u_1^2}{2}} = \frac{c_i^2}{u_1^2} = \frac{\Delta h_{is_{ts}}}{\frac{u_1^2}{2}}$$

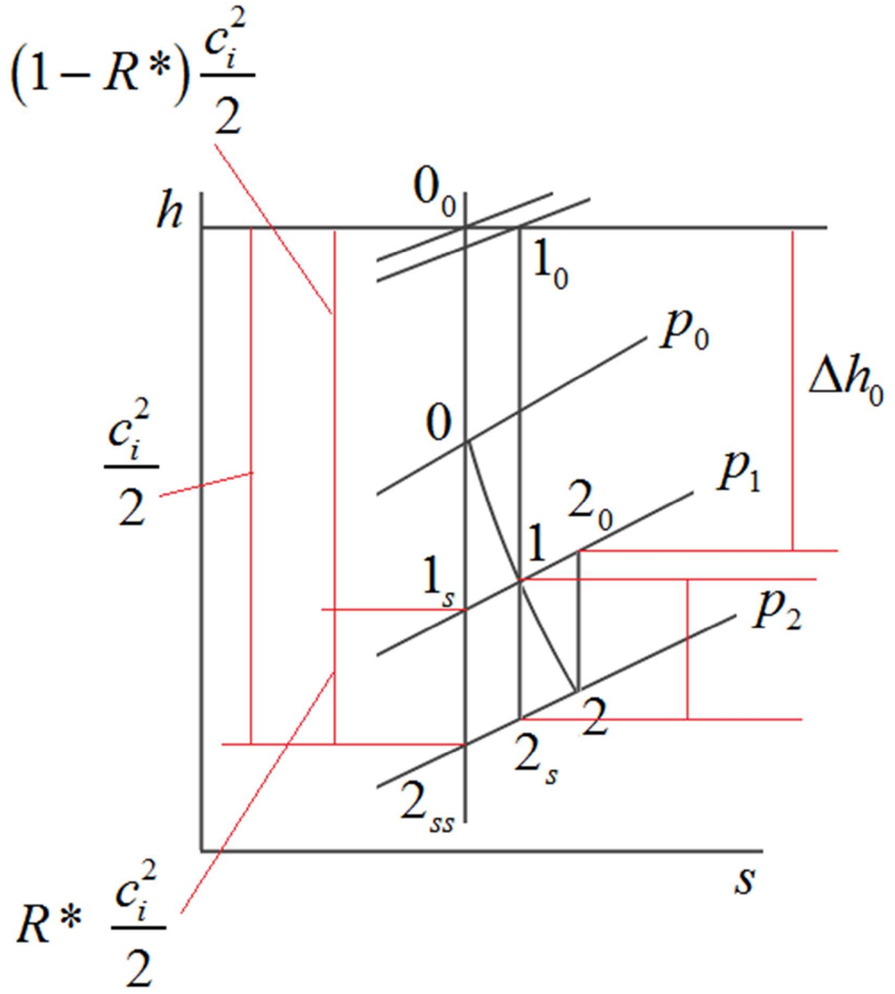
$$\frac{c_i^2}{2} = \psi \frac{u_1^2}{2}\frac{a_{0_0}^2}{a_{0_0}^2} = \frac{\psi}{2} M_u^2 \left(k-1\right) h_{0_0}$$

Calcolo delle proprietà termodinamiche nell'attraversamento della turbina

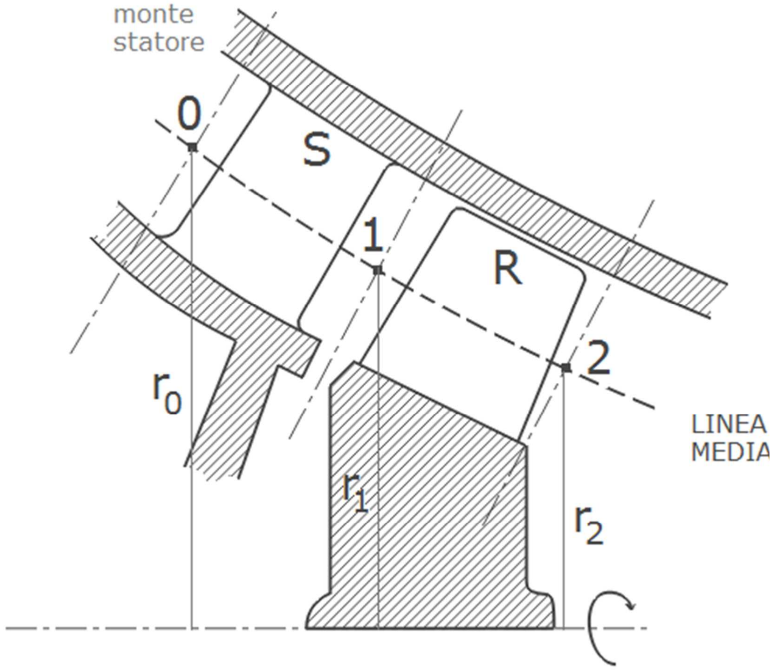


$$h_{1s} = h_{0_0} - \left(1 - R^*\right)\frac{c_i^2}{2} = h_{0_0}\left[1 - \left(1 - R^*\right)\frac{k-1}{2}\psi M_u^2\right]$$

$$h_{2ss} = h_{0_0} - \frac{c_i^2}{2} = h_{0_0}\left[1 - \frac{k-1}{2}\psi M_u^2\right]$$

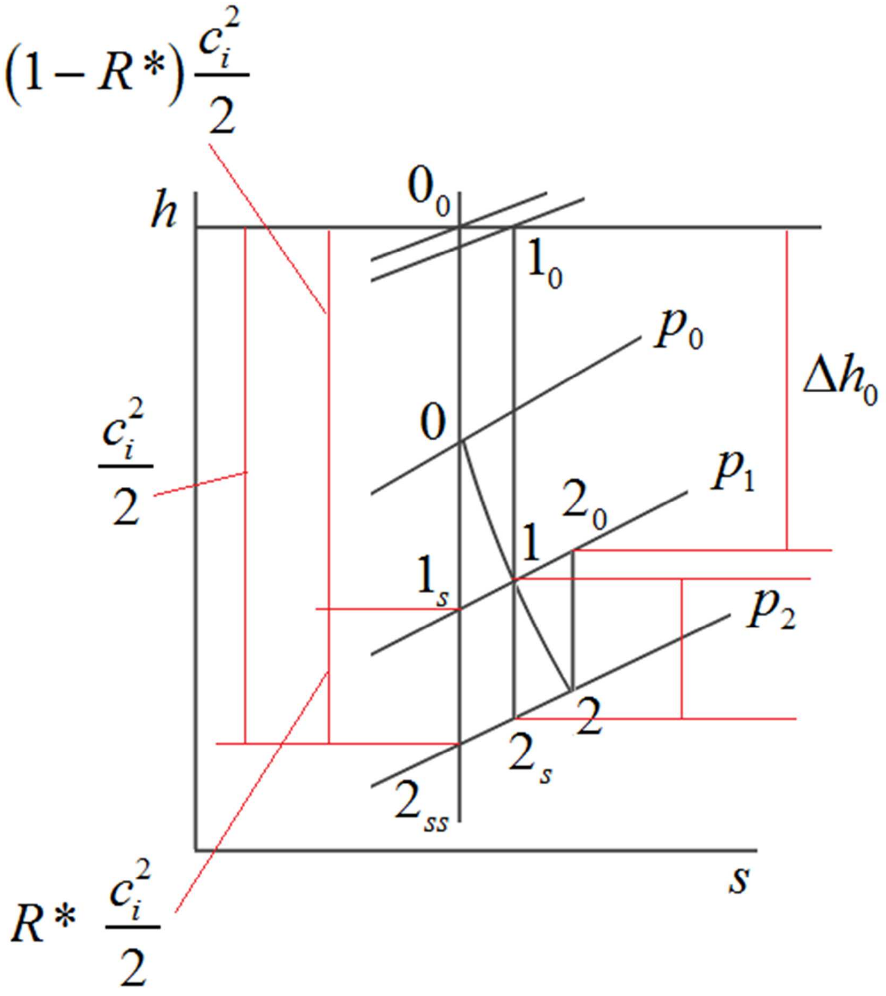


Calcolo delle proprietà termodinamiche nell’attraversamento della turbina



$$\frac{c_1^2}{2} = \eta_S \frac{c_i^2}{2}\left(1-R^*\right)$$

$$h_1 = h_{0_0} - \frac{c_1^2}{2} = h_{0_0}\left[1-\left(1-R^*\right)\frac{k-1}{2}\eta_S \psi M_u^2\right]$$



$$h_2 = h_{0_0} - \Delta h_0 - \frac{c_2^2}{2} = h_{0_0}\left[1-\left(\eta_{T,S}+\frac{C_2^2}{\psi}\right)\frac{k-1}{2}\psi M_u^2\right]$$