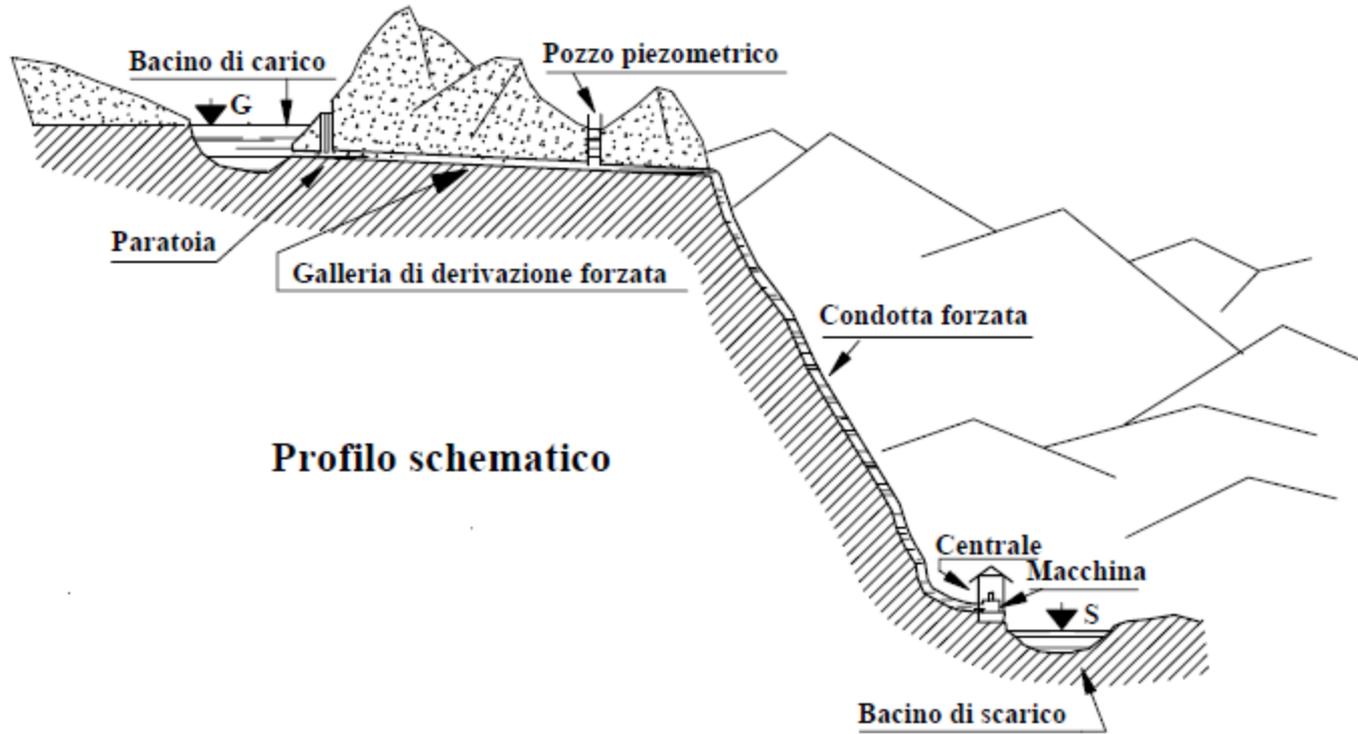


# **Sistema per lo sfruttamento dell'energia idraulica**

## IMPIANTI CON TURBINA IDRAULICA

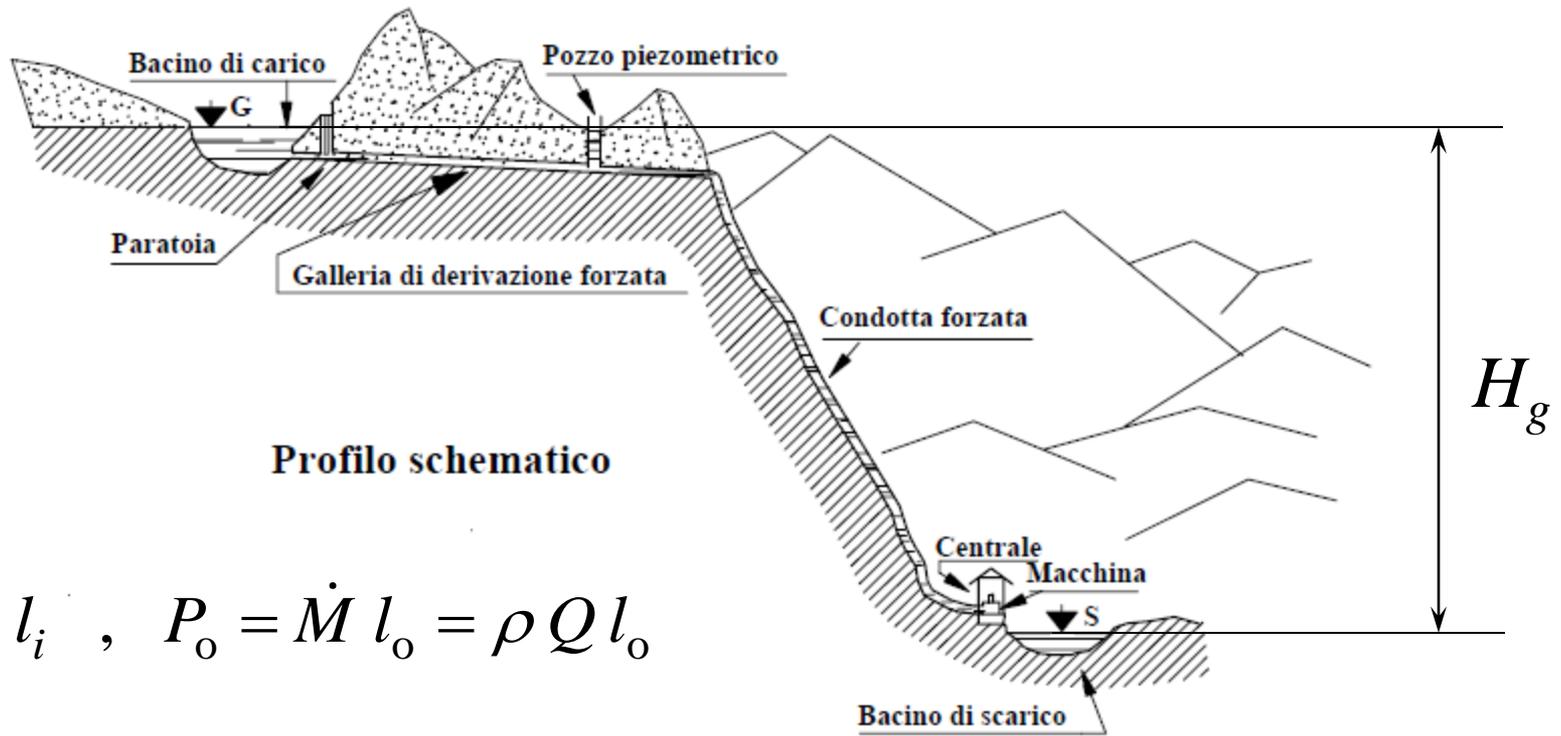


**Profilo schematico**

Visione schematica di un impianto per lo sfruttamento dell'energia idrica.

$$l_i = \frac{V_G^2 - V_S^2}{2} + \frac{p_G - p_S}{\rho} + g(z_G - z_S) - R_{G-S} \cong g H_g - R_{G-S}$$

### IMPIANTI CON TURBINA IDRAULICA



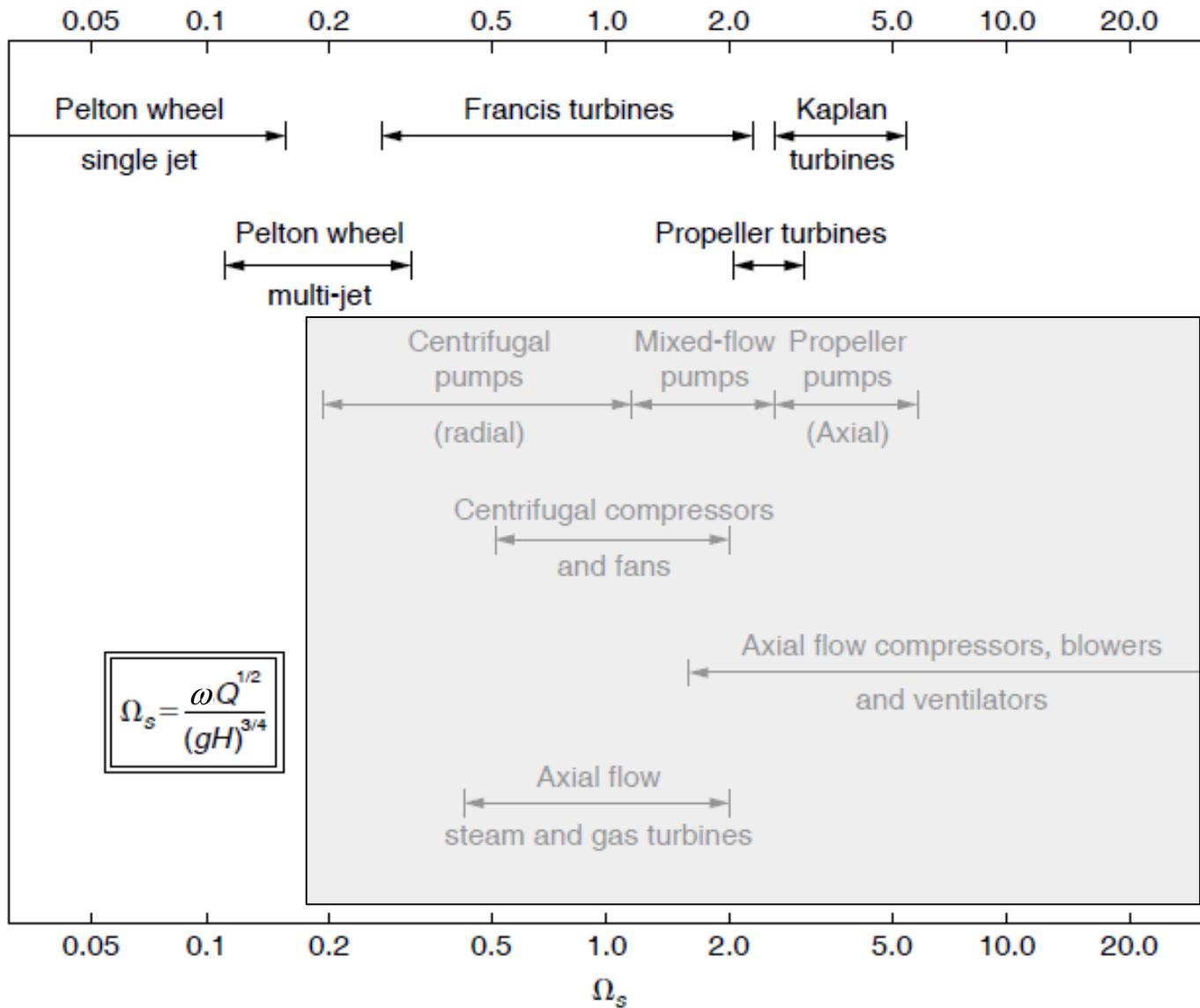
Profilo schematico

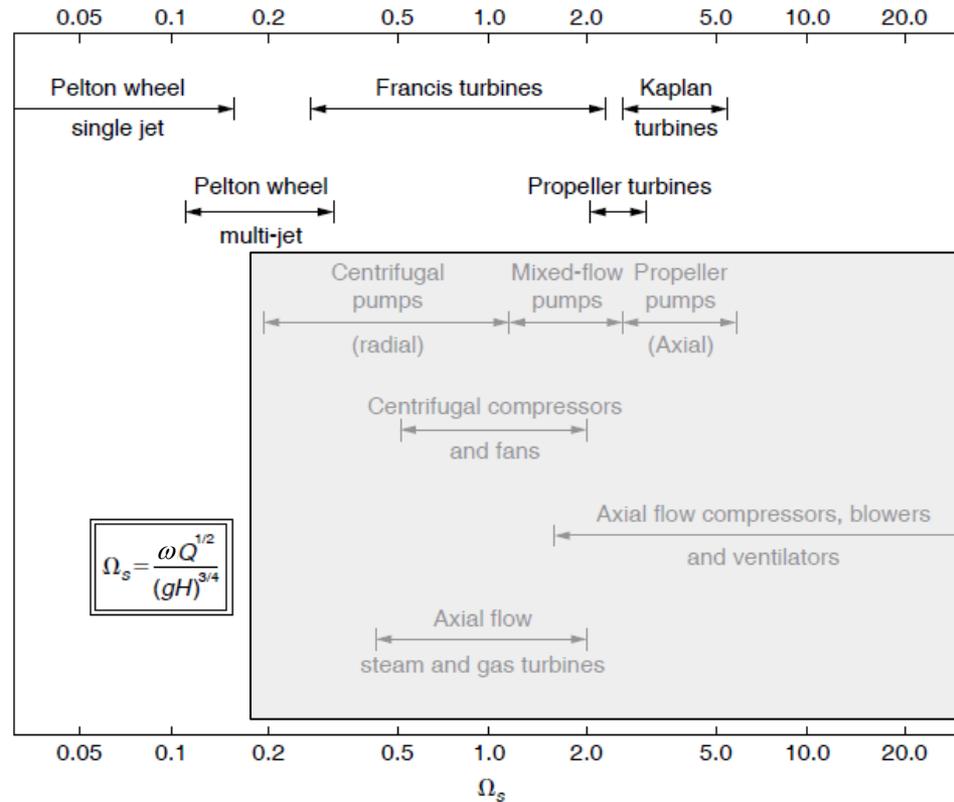
Visione schematica di un impianto per lo sfruttamento dell'energia idrica.

$$l_o = \eta_o l_i, \quad P_o = \dot{M} l_o = \rho Q l_o$$

$$\eta_{\text{imp}} = \frac{P_o}{\rho Q g H_g} = \eta_o \frac{g H_g - R_{G-S}}{g H_g} = \eta_o \left( 1 - \frac{R_{G-S}}{g H_g} \right)$$

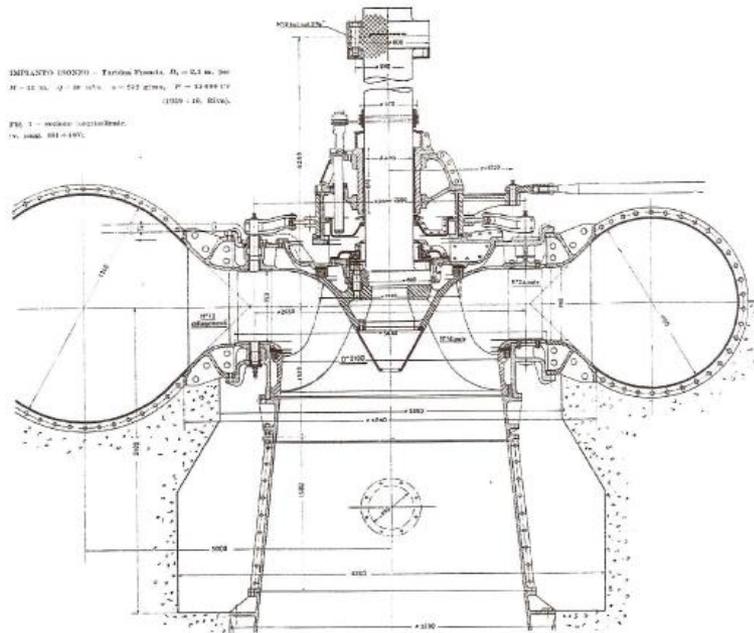
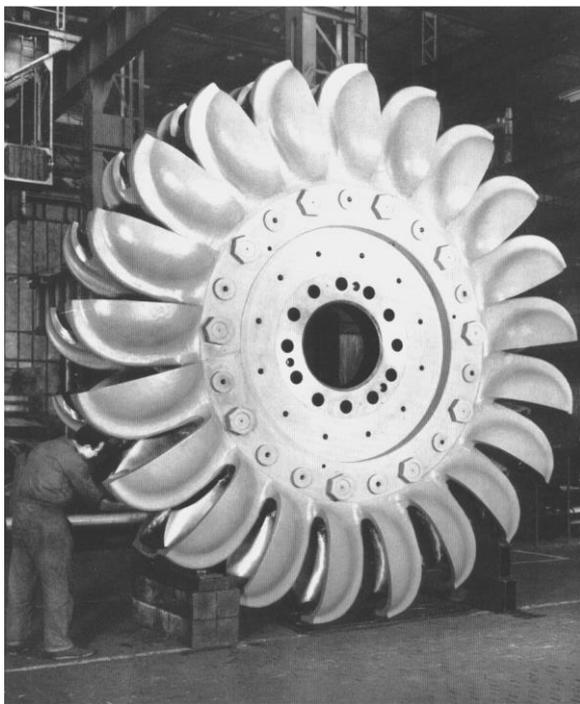
# Turbine idrauliche





$$\Omega_P = \frac{\hat{p}^{1/2}}{\psi^{5/4}} = \frac{P^{1/2}}{\rho^{1/2} \omega^{3/2} D^{5/2}} \frac{\omega^{5/2} D^{5/2}}{(gH)^{5/4}} = \omega \frac{P^{1/2}}{\rho^{1/2} (gH)^{5/4}}$$

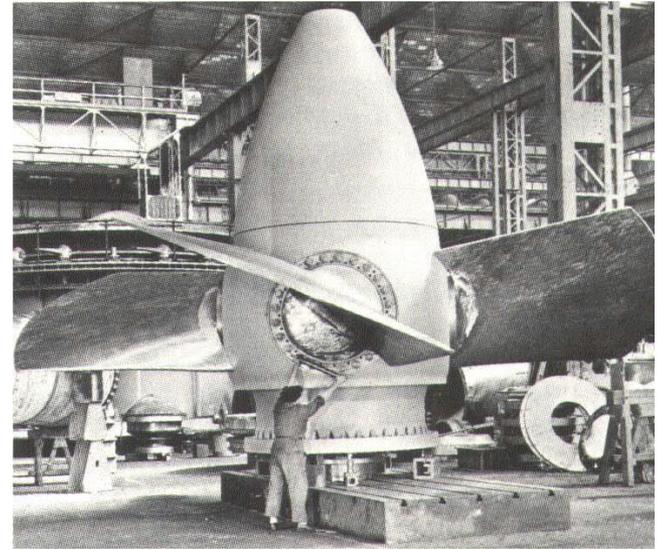
$$n_s = n_p = N \frac{P^{1/2}}{H^{5/4}} = \frac{N}{H} \sqrt{\frac{P}{\sqrt{H}}}$$



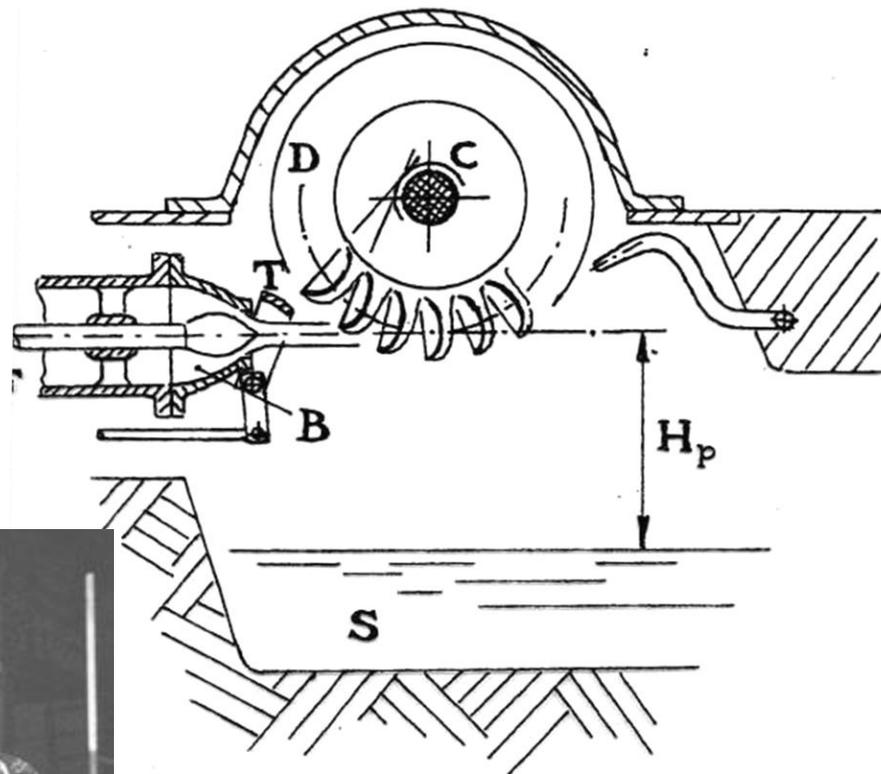
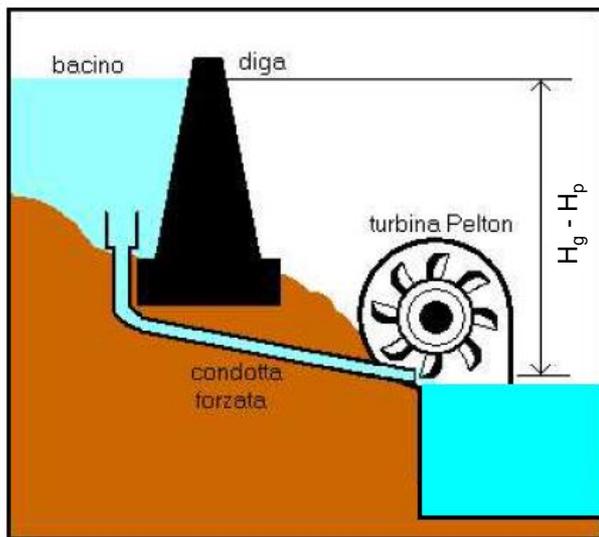
Turbina Francis

Rotore turbina Pelton

Rotore turbina Kaplan

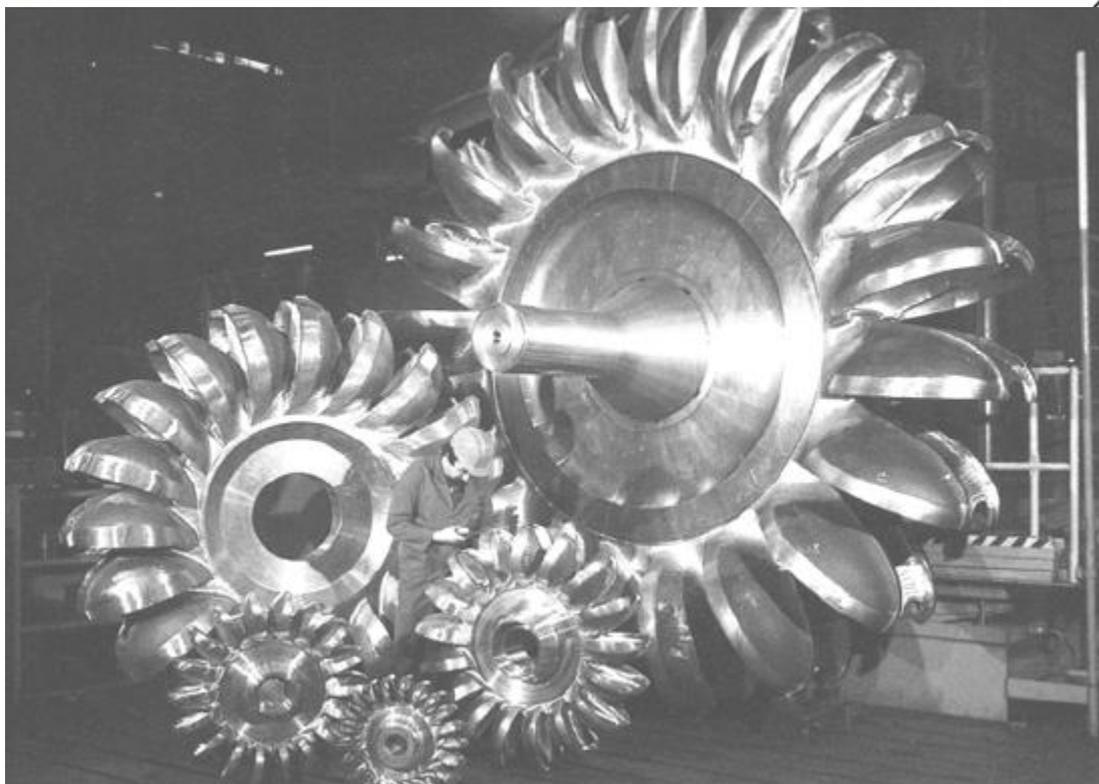


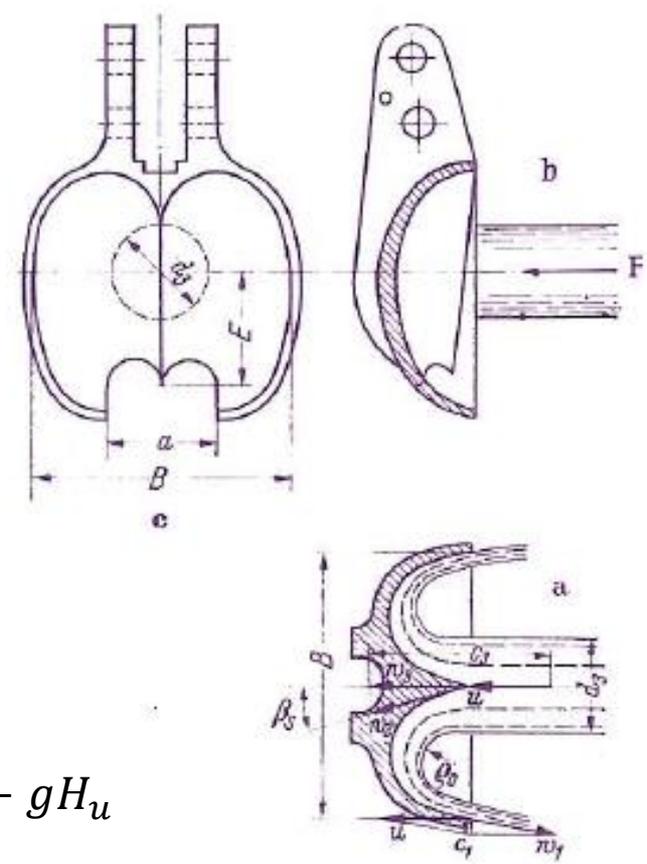
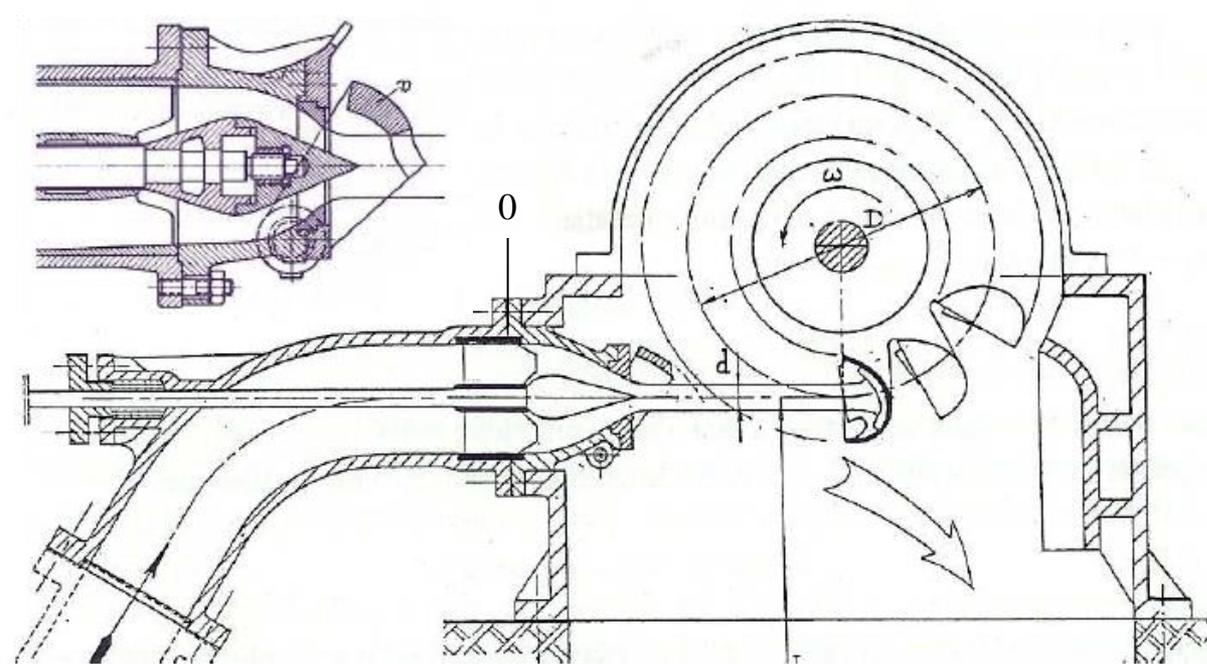
# Turbina Pelton



$$H_u = H_g - H_p - \frac{R_{cond}}{g}$$

$$H_u = H_g - H_p - H_{cond}$$



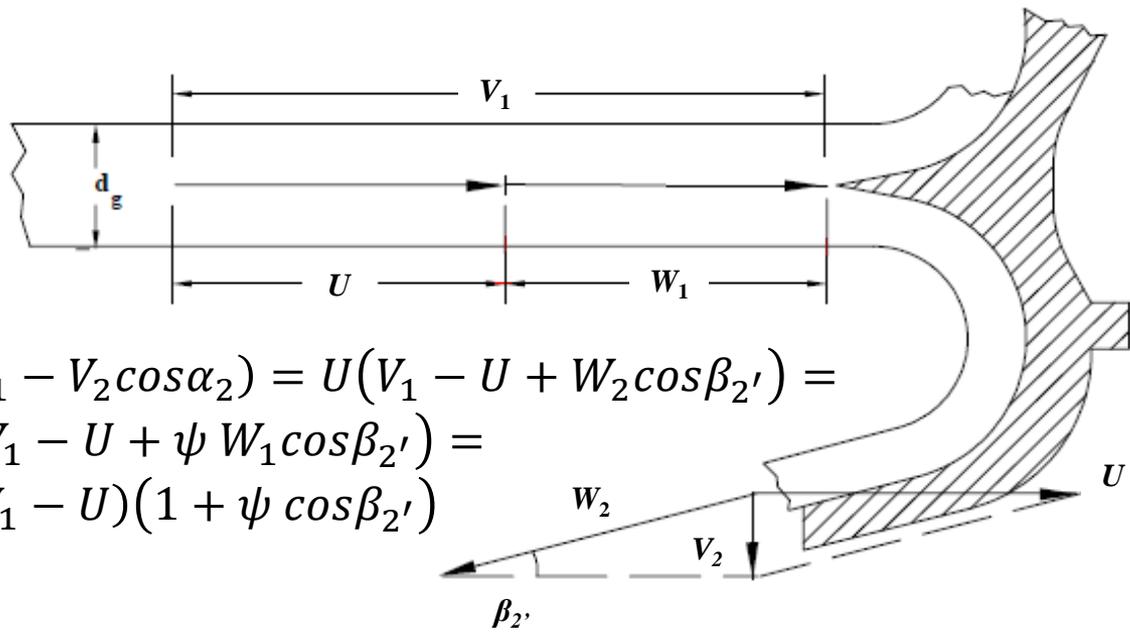
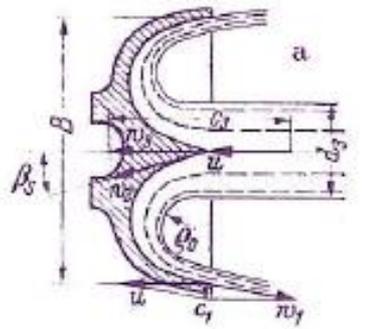
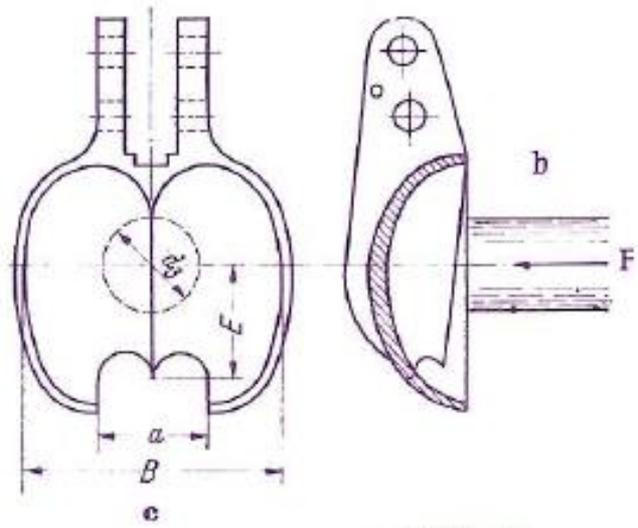
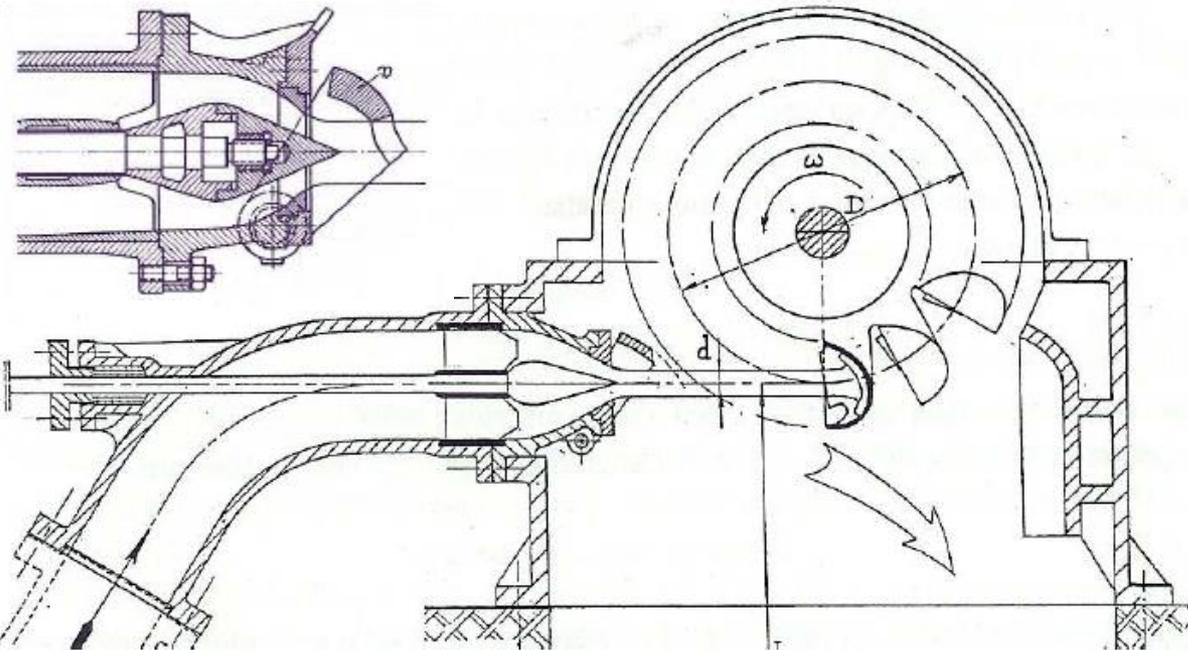


$$\frac{V_0^2}{2} + \frac{p_0}{\rho} = \frac{V_G^2}{2} + \frac{p_G}{\rho} + g(H_g - H_p - H_{cond}) \cong \frac{p_G}{\rho} + gH_u$$

$$\frac{V_{1t}^2}{2} + \frac{p_s}{\rho} = \frac{V_0^2}{2} + \frac{p_0}{\rho} \cong \frac{p_s}{\rho} + gH_u$$

$$V_{1t} = \sqrt{2gH_u} \quad , \quad V_1 = \varphi V_{1t} = \varphi \sqrt{2gH_u} \quad , \quad \varphi < 1$$

$$\eta_b = \frac{V_1^2}{2gH_u} = \varphi^2$$



$$\begin{aligned}
 l_i &= U(V_1 - V_2 \cos \alpha_2) = U(V_1 - U + W_2 \cos \beta_{2'}) = \\
 &= U(V_1 - U + \psi W_1 \cos \beta_{2'}) = \\
 &= U(V_1 - U)(1 + \psi \cos \beta_{2'})
 \end{aligned}$$

$$Q = V_1 \frac{\pi d^2}{4} \quad , \quad V_1 = \varphi V_{1t} = \varphi \sqrt{2g H_u} = \varphi \sqrt{2g (H_g - H_p - H_{cond})}$$

$$\eta_b = \frac{V_1^2}{2g H_u} = \varphi^2$$

$$\eta_i = \frac{l_i}{\frac{V_1^2}{2}} = 2 \frac{U(V_1 - U)(1 + \psi \cos\beta_{2'})}{V_1^2} =$$

$$= 2 \frac{U}{V_1} \left(1 - \frac{U}{V_1}\right) (1 + \psi \cos\beta_{2'}) \quad , \quad \left(\frac{U}{V_1}\right)_{\eta_{iMAX}} \approx 0.5$$

$$\eta_o = \frac{l_o}{l_i} = \frac{P_o}{P_i} = 1 - \frac{P_{md}}{P_i} - \frac{P_{aus}}{P_i}$$

$$\eta_{tot} = \frac{P_o}{\rho Q g H_u} = \eta_o \eta_i \eta_b \quad , \quad P_o = \eta_{tot} \rho Q g H_u$$

$$\eta_{imp} = \frac{P_o}{\rho Q g H_g} = \frac{P_o}{\rho Q g H_u} \cdot \frac{H_u}{H_g} = \eta_{tot} \eta_{inst}$$

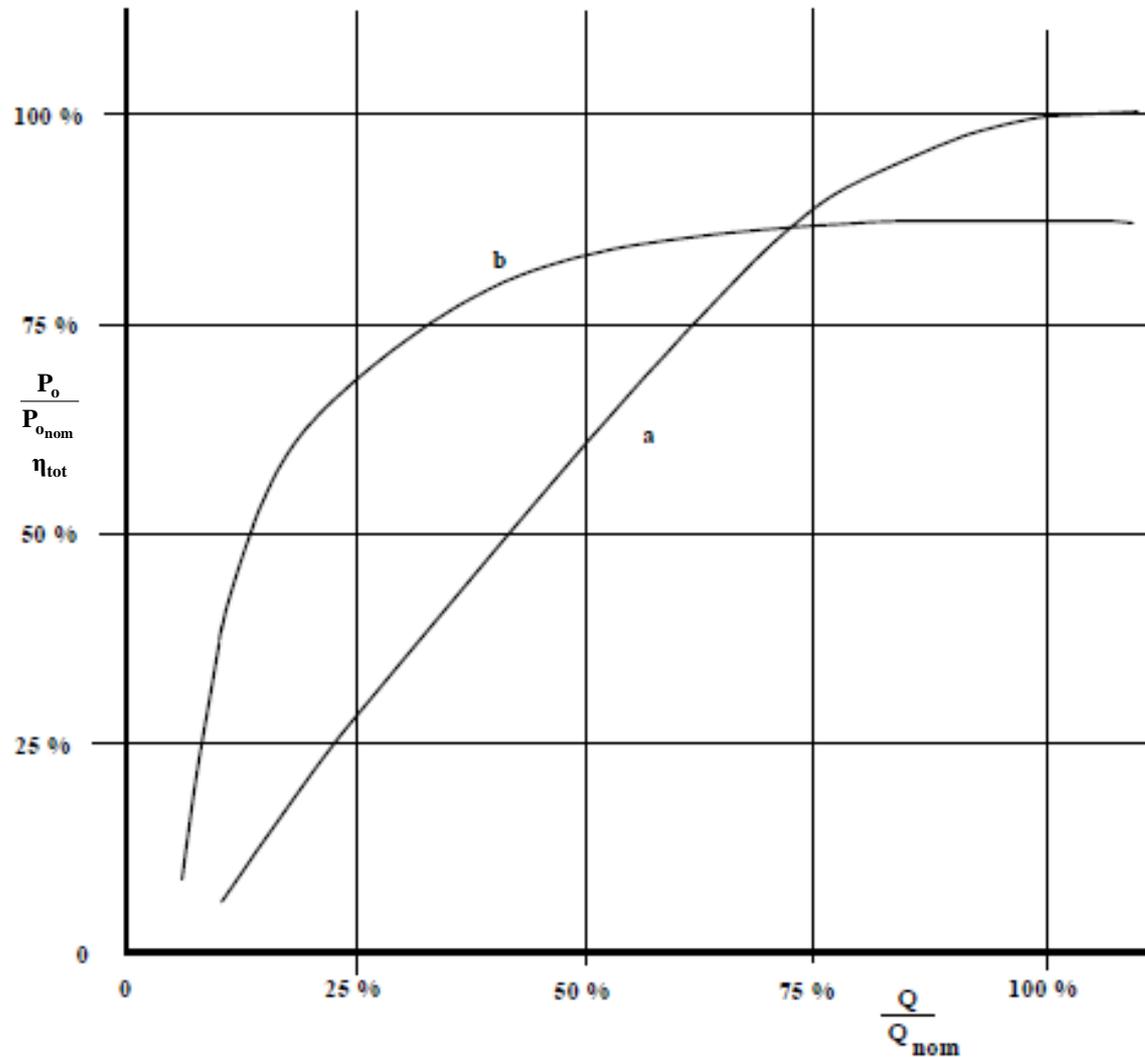
$$P_o = \eta_{tot} \rho Q g H_u = \eta_o \eta_i \eta_b \rho Q g H_u = \sqrt{2} \rho \eta_o \eta_i \frac{\pi d^2}{4} \varphi^3 [g(H_g - H_p - H_{cond})]^{3/2}$$

In prima approssimazione, variando l'area del bocchello ( $\pi d^2/4$ ) senza incremento delle perdite,  $\eta_{tot}$  si manterrebbe costante e  $P_o$  varierebbe proporzionalmente al variare della portata  $Q$

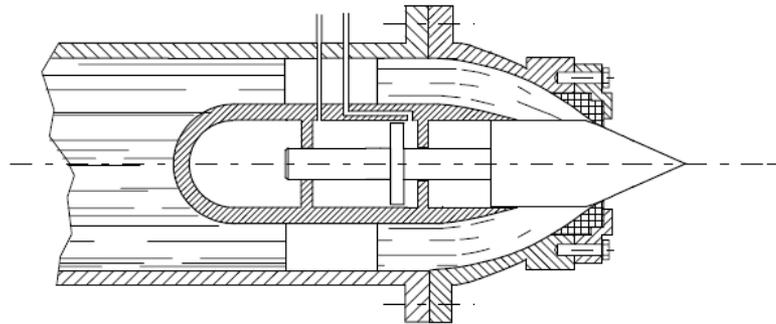
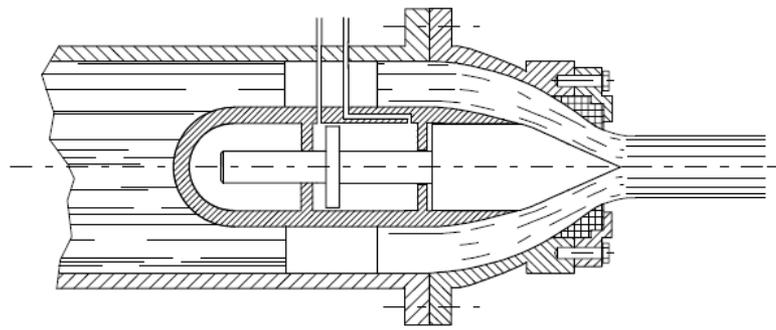
In realtà, riducendo l'area del bocchello ( $\pi d^2/4$ ):

- si riduce la portata  $Q$  e, quindi, la velocità di attraversamento della condotta e la perdita nella condotta ( $H_{cond}$ )  $\rightarrow H_u$  cresce leggermente
- si riduce  $\varphi$
- si riduce  $\eta_o$ , in quanto  $P_{md}$  e  $P_{aus}$  variano meno di  $P_i$
- in  $\eta_i$  si modifica il valore di  $\psi \cos \beta_2$ ,

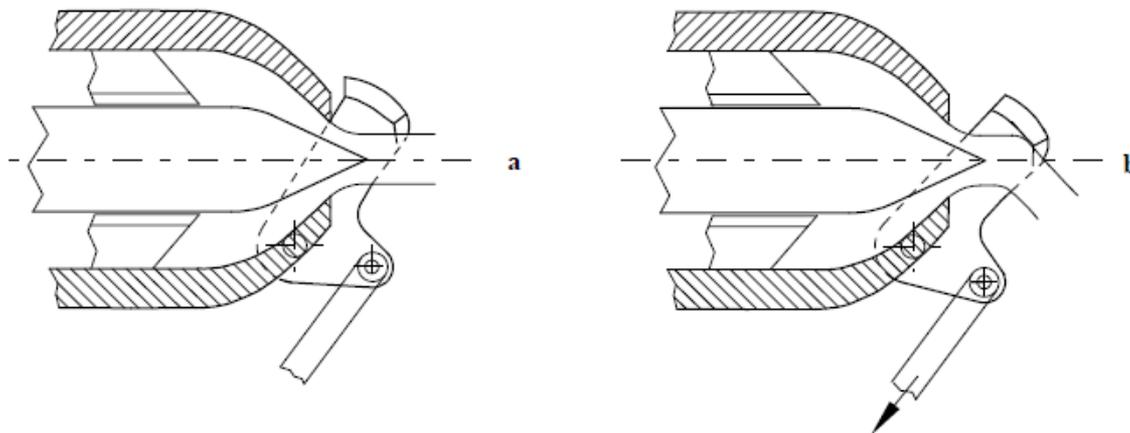
$$P_o = \eta_{tot} \rho Q g H_u = \eta_o \eta_i \eta_b \rho Q g H_u = \sqrt{2} \rho \eta_o \eta_i \frac{\pi d^2}{4} \varphi^3 [g(H_g - H_p - H_{cond})]^{3/2}$$



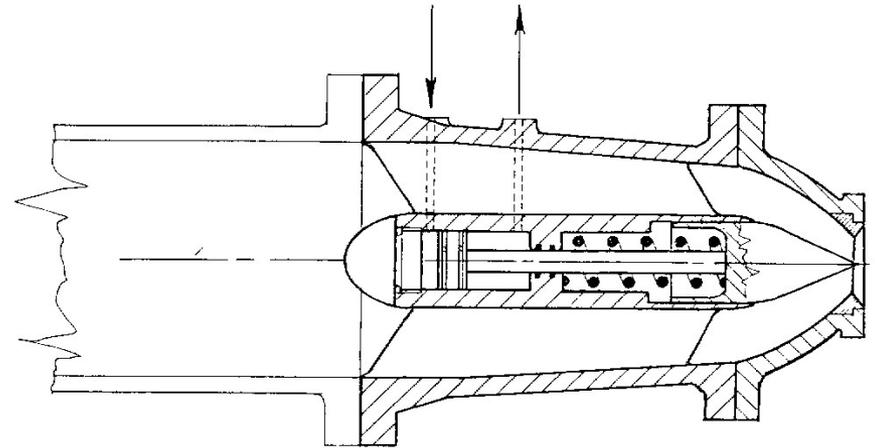
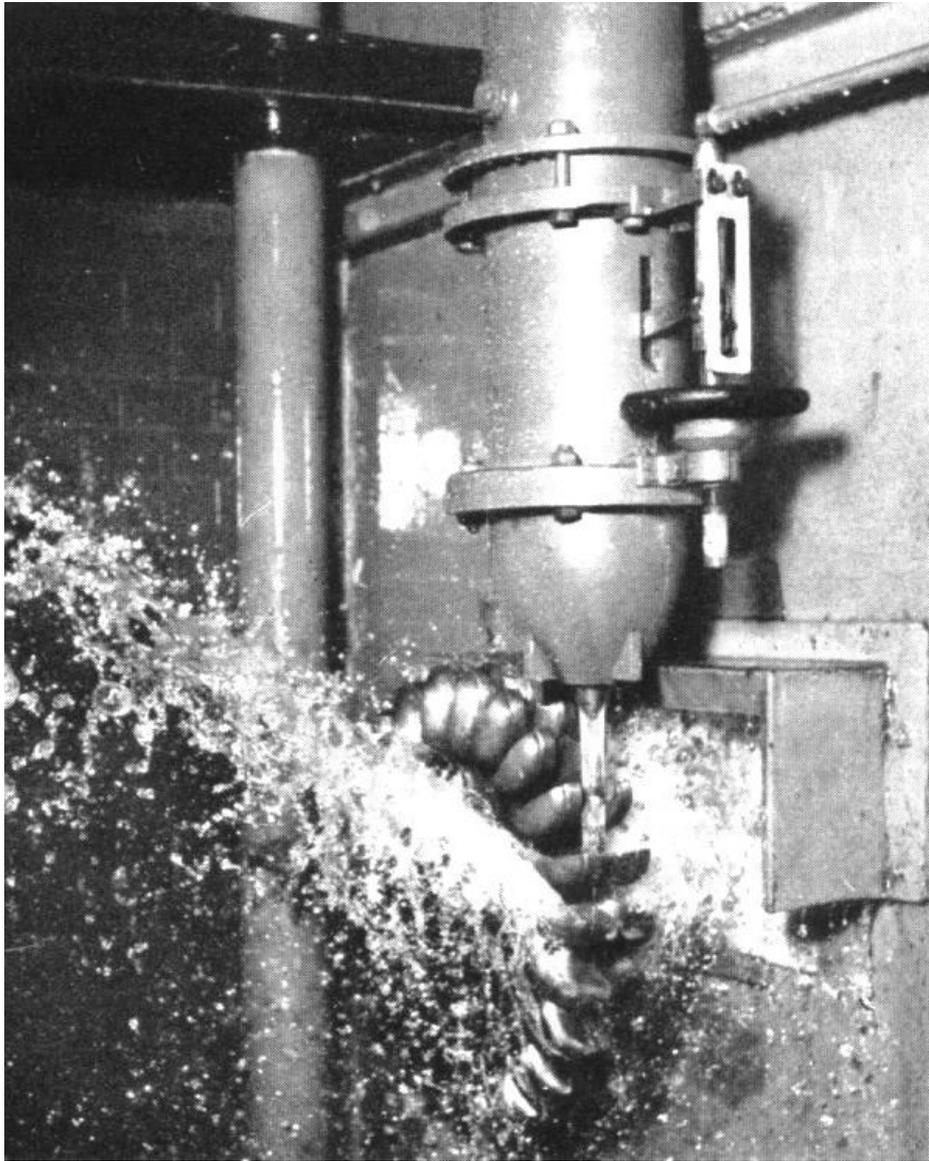
Andamento del rendimento (curva b) e della potenza (curva a), quest'ultima rispetto alle condizioni nominali di funzionamento, al variare della portata  $Q_v$  rispetto a quella nominale in una turbina Pelton.

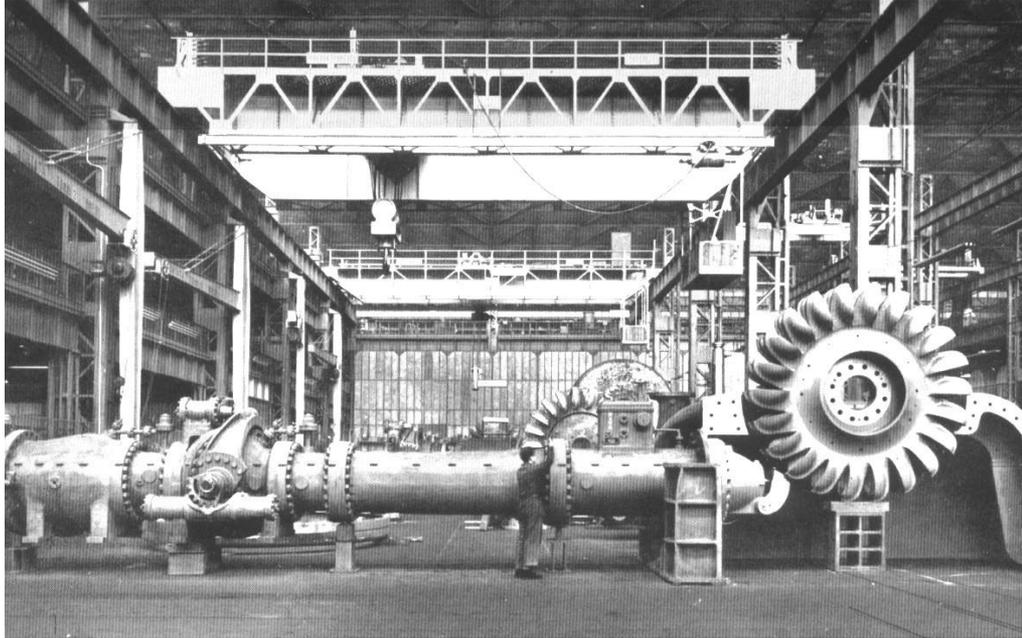


Schema di ugello Doble:  
 a : in condizioni di massima apertura (portata max).  
 b : in condizioni di chiusura (portata nulla).



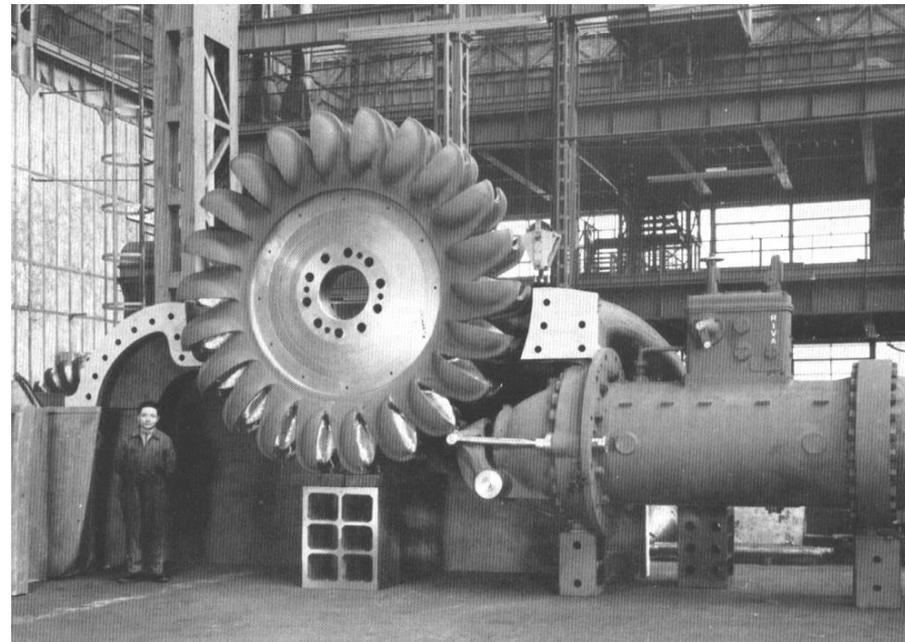
Visione schematica del funzionamento del tegolo deviatore.

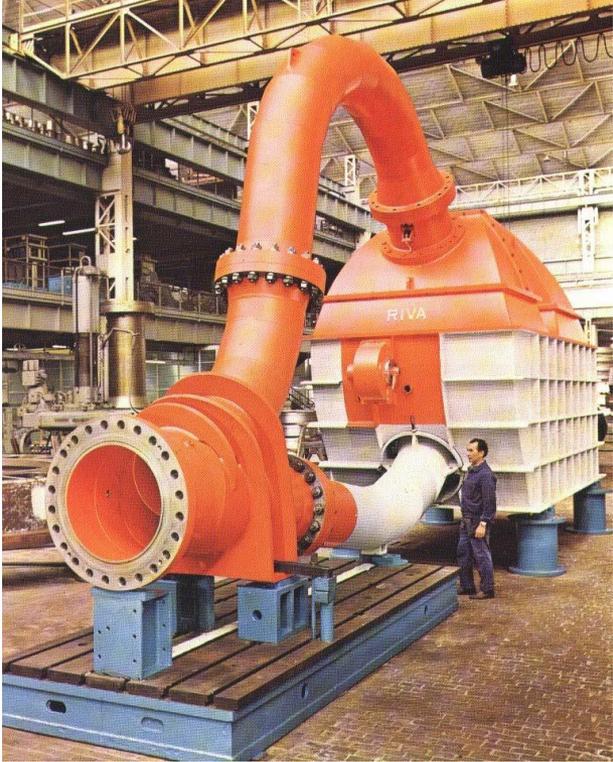




H	1030	m
Q	6.5	m <sup>3</sup> /s
P	57.1	MW
n	500	giri/min
d	173	mm
D	2600	mm

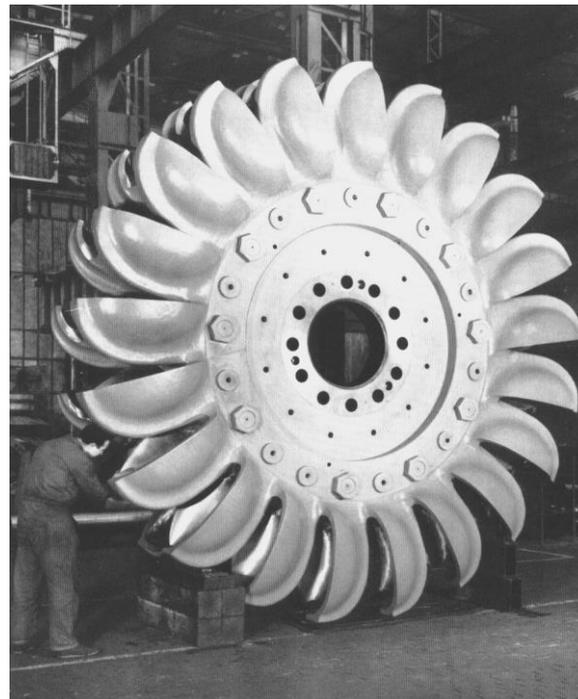
H	951	m
Q	6.5	m <sup>3</sup> /s
P	53.3	MW
n	500	giri/min
z	22	-
d	181	mm
D	2450	mm





H	612	592	m
Q	4.20	4.13	m <sup>3</sup> /s
P	22.19	21.11	MW
n	600	600	giri/min
nq	9.99	10.16	
D	2165	-	mm

H	721	m
Q	8.75	m <sup>3</sup> /s
P	55	MW
n	300	giri/min
d	310	mm
D	3650	mm
m	44	t
Z	21	-





Corso di “Macchine” – Pier Ruggero Spina (Laurea in Ingegneria Meccanica; Università degli Studi di Ferrara)

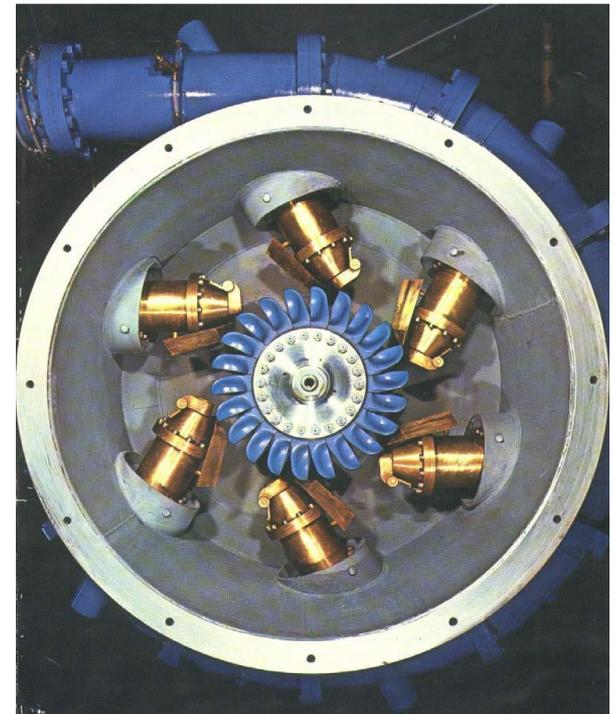
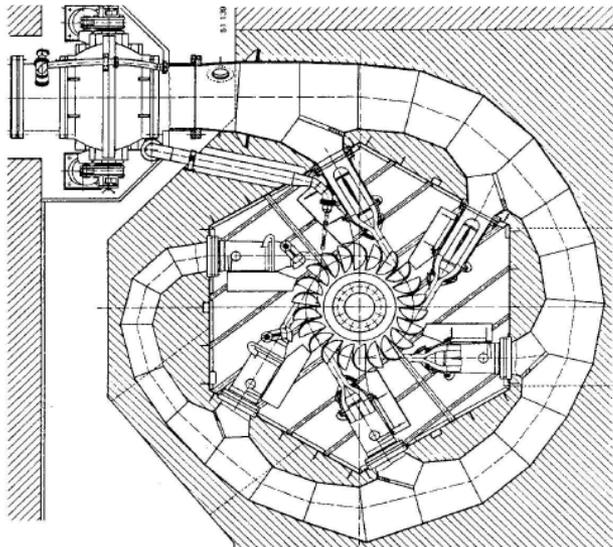
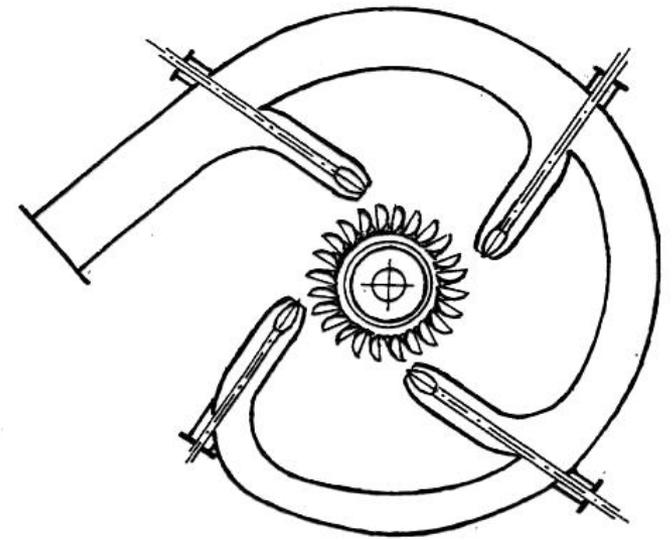
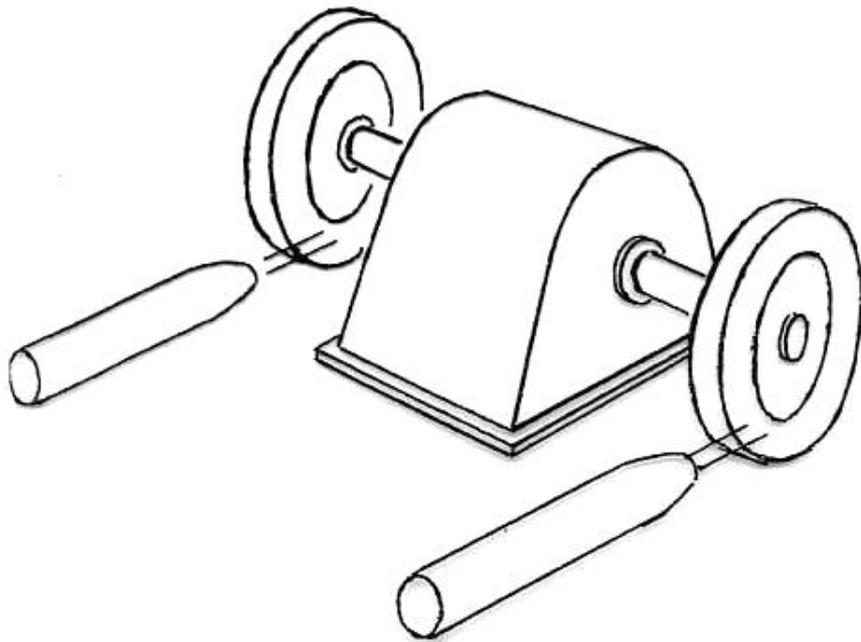
$$Q \propto d^2 \rightarrow D \propto d \propto \sqrt{Q}$$

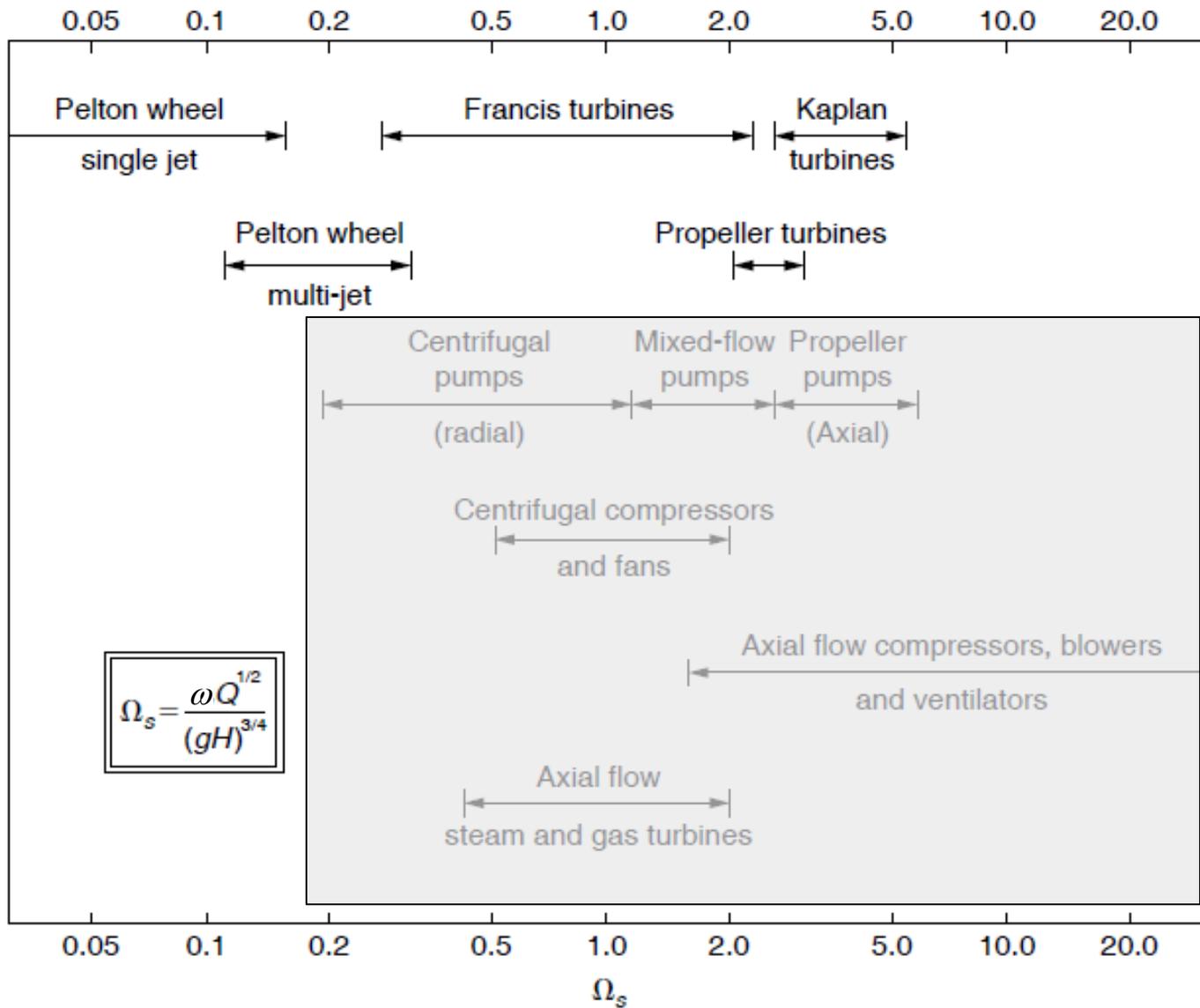
$$U \propto V_1 \propto \sqrt{H}$$

$$\left. \begin{array}{l} Q \uparrow \rightarrow d \uparrow \rightarrow D \uparrow \\ H \downarrow \rightarrow V_1 \downarrow \rightarrow U \downarrow \end{array} \right\} \rightarrow N \propto \frac{U}{D} \downarrow\downarrow$$

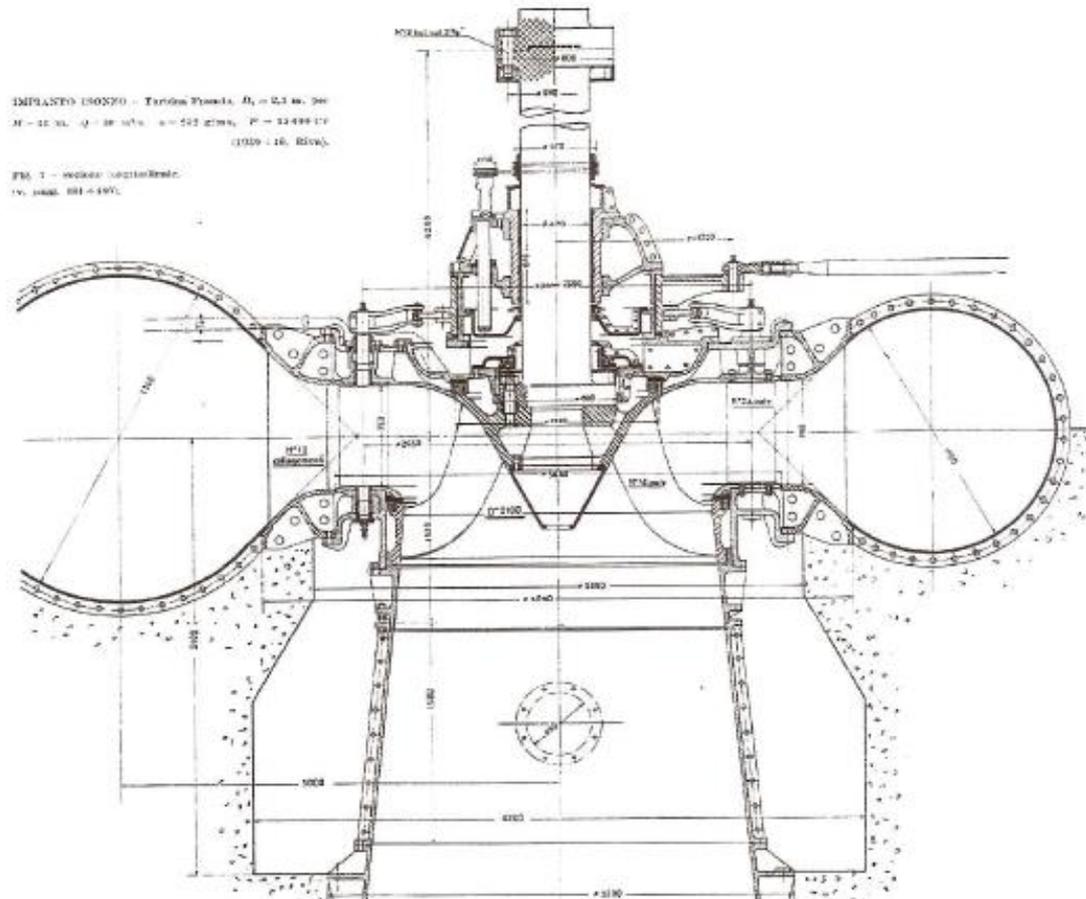
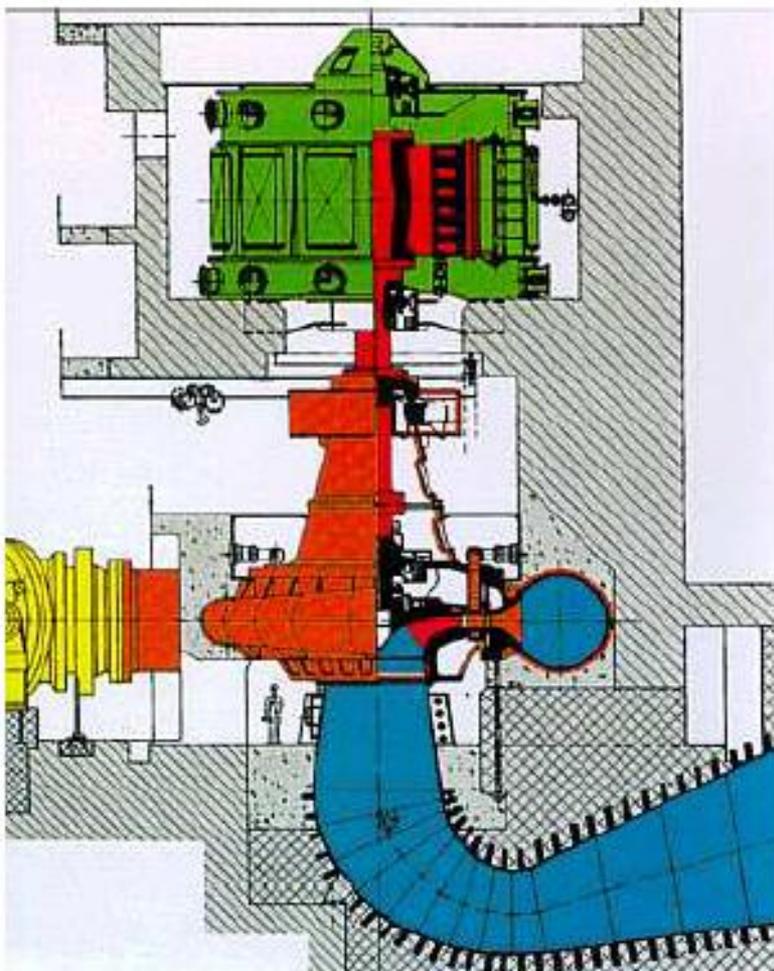
$$Q \propto n_{getti} d^2 \rightarrow D \propto d \propto \sqrt{\frac{Q}{n_{getti}}}$$

$$N \propto \sqrt{\frac{n_{getti}}{Q}}$$

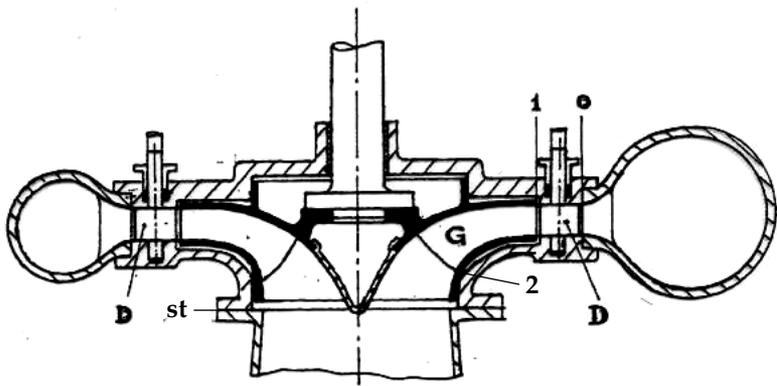




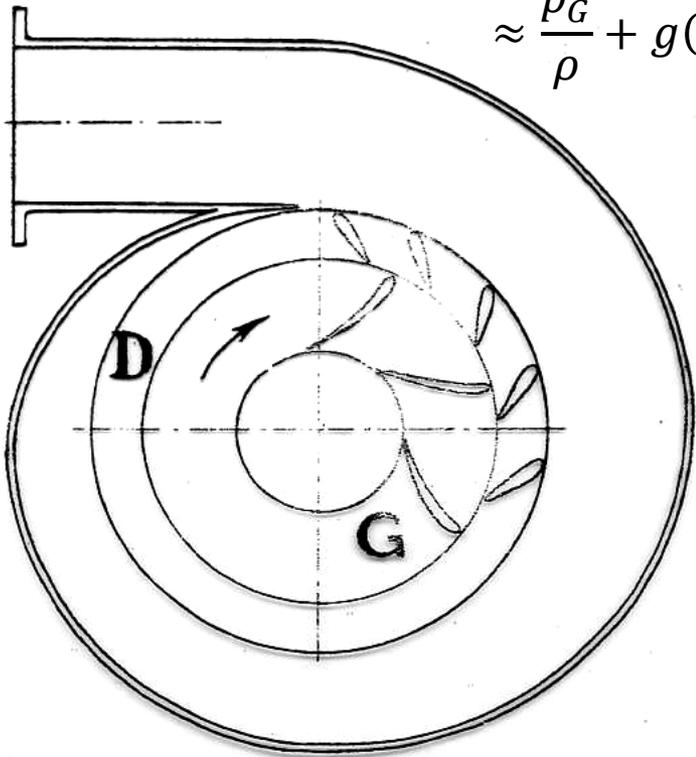
# Turbina Francis

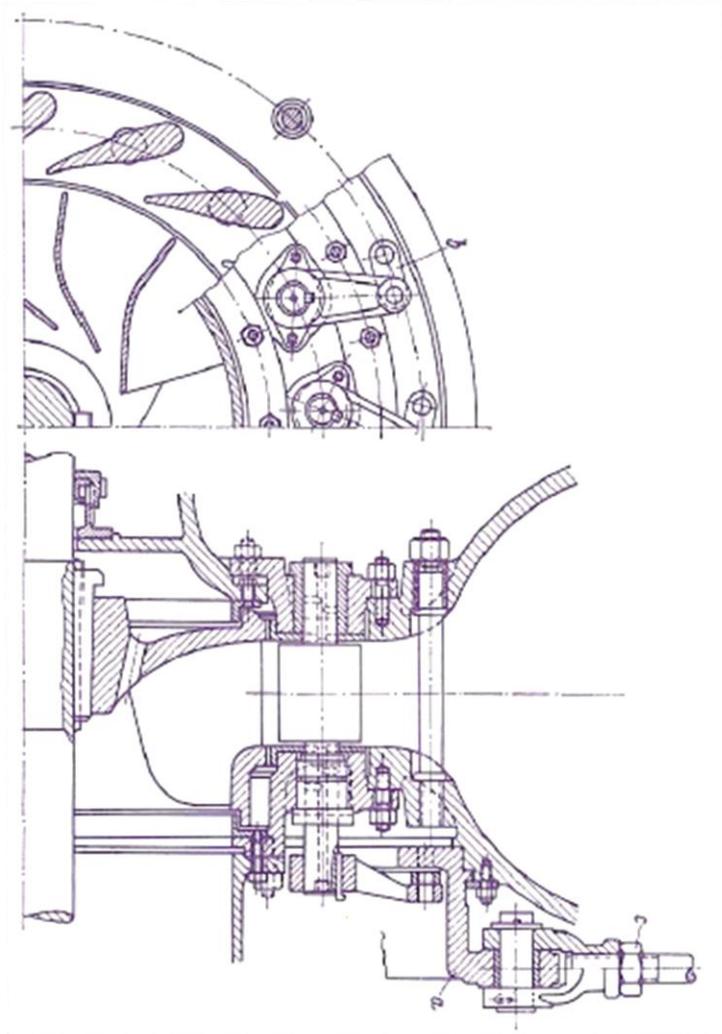
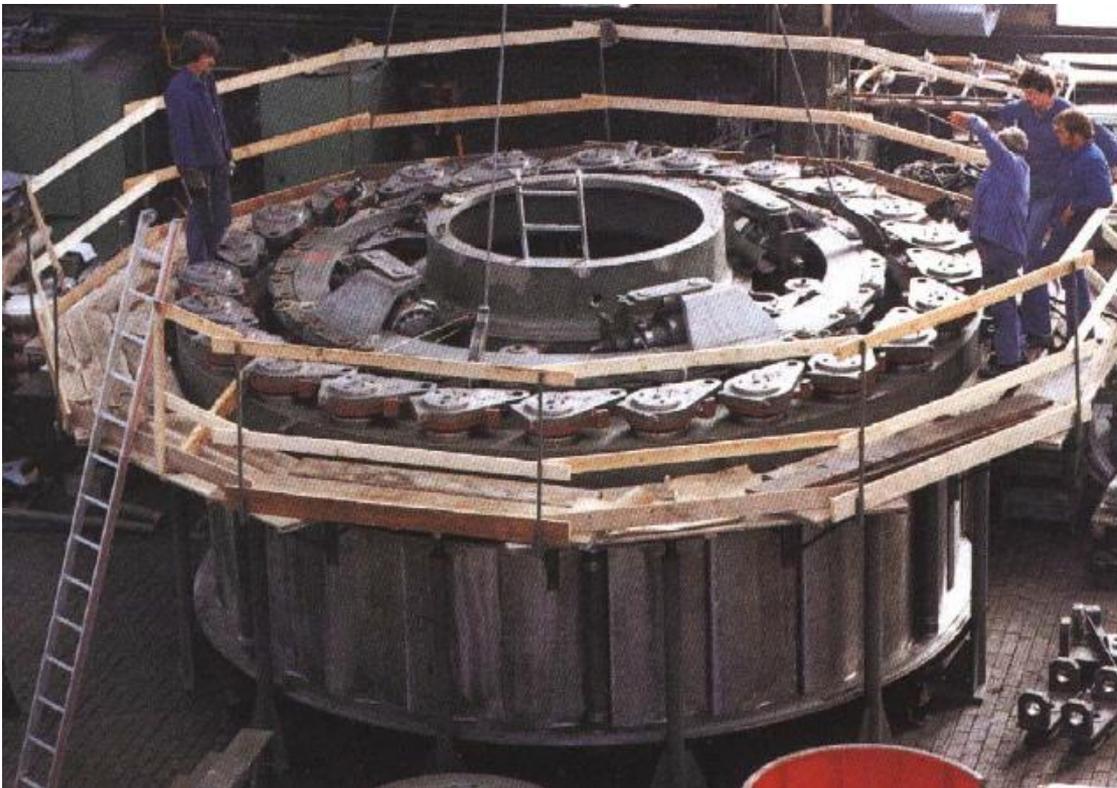


$$H_u = H_g - \frac{R_{cond}}{g} = H_g - H_{cond}$$

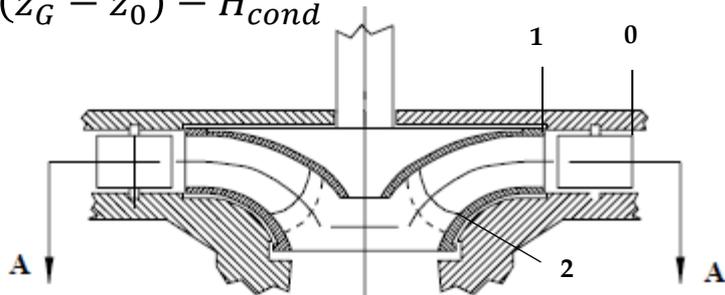


$$\frac{V_0^2}{2} + \frac{p_0}{\rho} = \frac{V_G^2}{2} + \frac{p_G}{\rho} + g(z_G - z_0) - H_{cond} \approx \frac{p_G}{\rho} + g(z_G - z_0) - H_{cond}$$

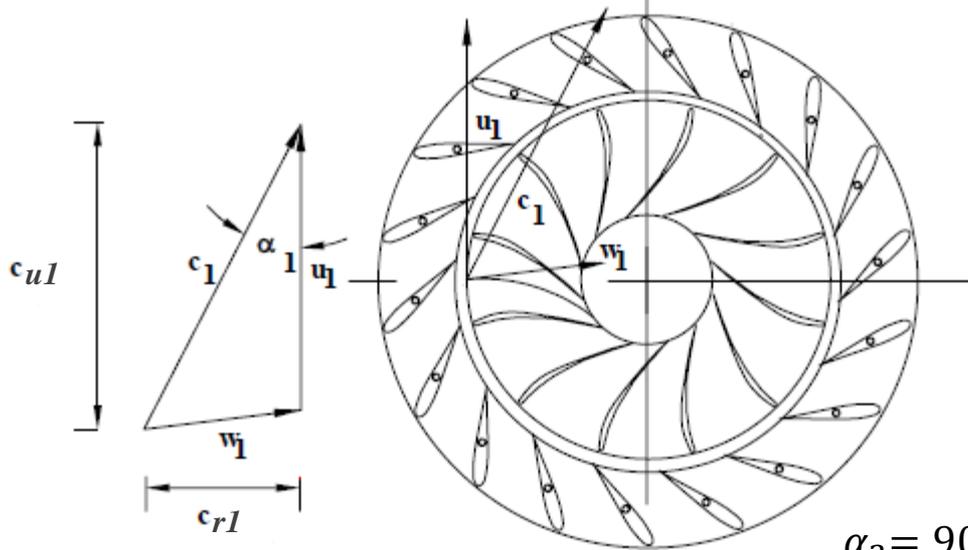
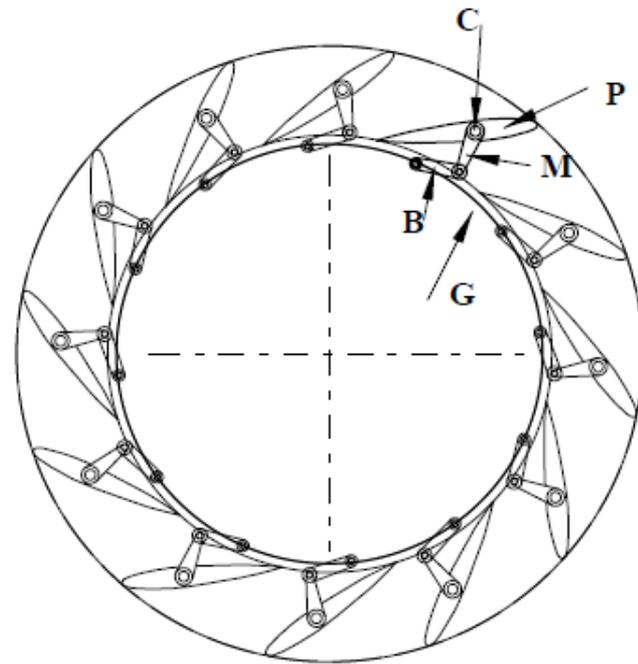




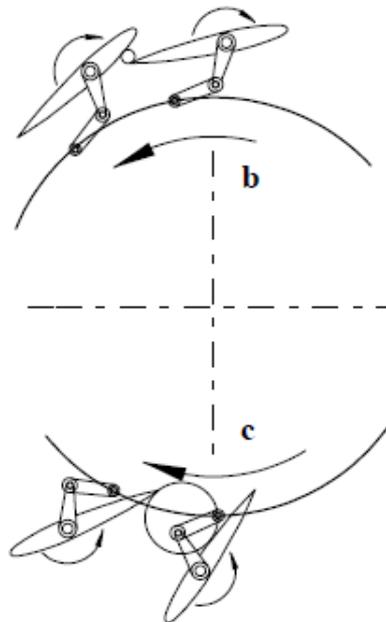
$$\frac{c_0^2}{2} + \frac{p_0}{\rho} \approx \frac{p_G}{\rho} + g(z_G - z_0) - H_{cond}$$



$$l_i = \frac{c_1^2 - c_2^2}{2} + \frac{w_2^2 - w_1^2}{2} + \frac{u_1^2 - u_2^2}{2} = u_1 c_1 \cos \alpha_1 - u_2 c_2 \cos \alpha_2$$



$$\alpha_2 = 90^\circ \rightarrow l_i = u_1 c_{u1}$$

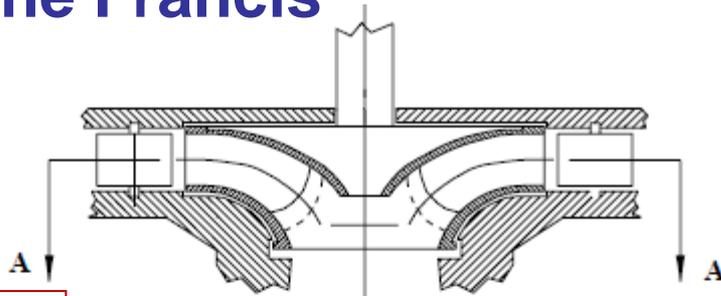


$$Q = c_{r1} A_p = c_{r1} \pi D_1 b_1 \xi_1 \quad \text{sezione A-A}$$

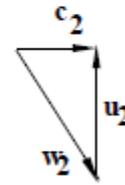
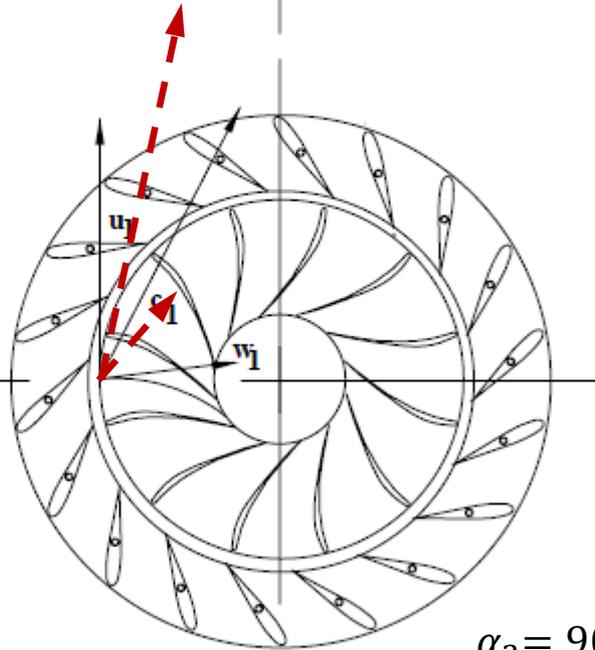
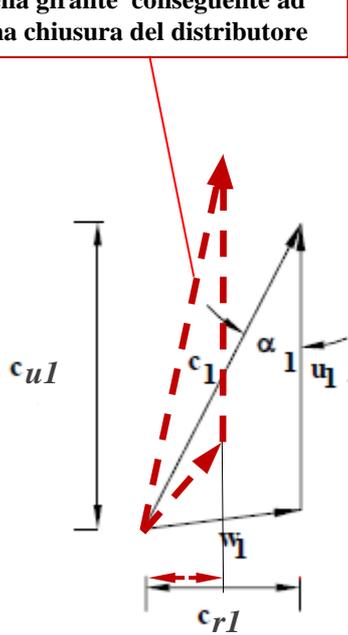
Triangoli di velocità di una Francis, in ingresso e uscita.

Per evidenti motivi grafici, nella rappresentazione nella sezione A-A il triangolo all'ingresso non si riferisce allo stesso condotto di quello all'uscita.

# Regolazione Francis

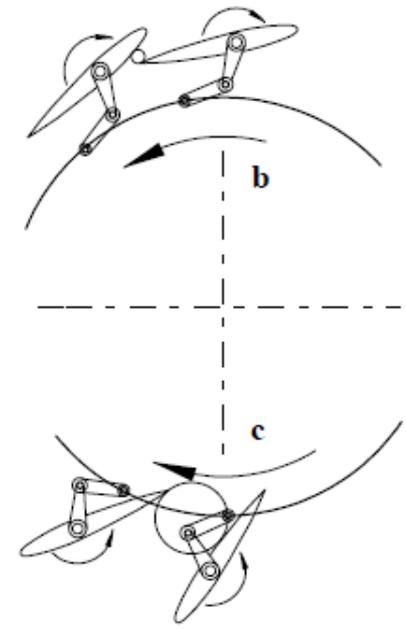
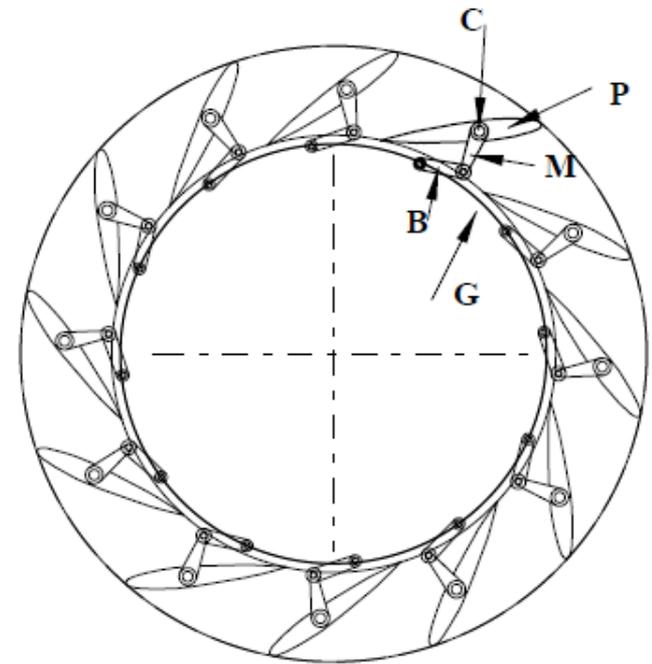


Velocità assoluta all'ingresso della girante conseguente ad una chiusura del distributore



$$\alpha_2 = 90^\circ \rightarrow l_i = u_1 c_{u1}$$

$$Q = c_{r1} A_p = c_{r1} \pi D_1 b_1 \xi_1 \quad \text{sezione A-A}$$



Triangoli di velocità di una Francis, in ingresso e uscita.

Per evidenti motivi grafici, nella rappresentazione nella sezione A-A il triangolo all'ingresso non si riferisce allo stesso condotto di quello all'uscita.

$$Q = c_{r1} A_p = c_{r1} \pi D_1 b_1 \xi_1$$

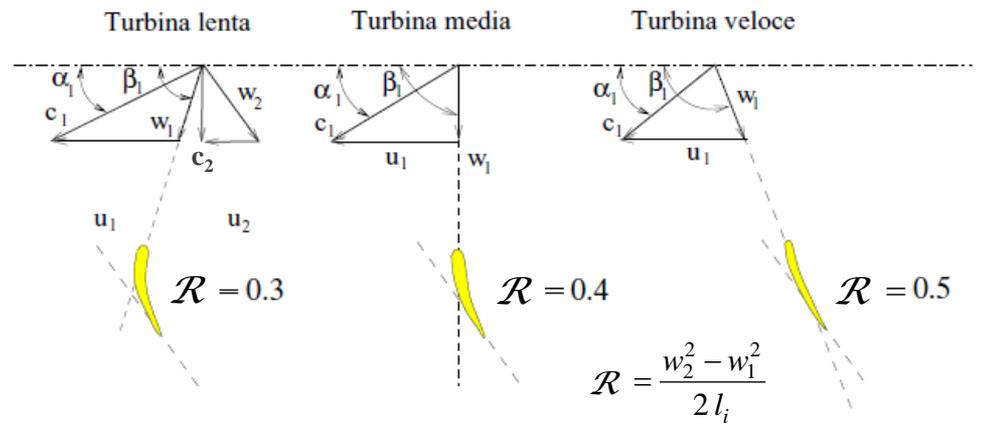
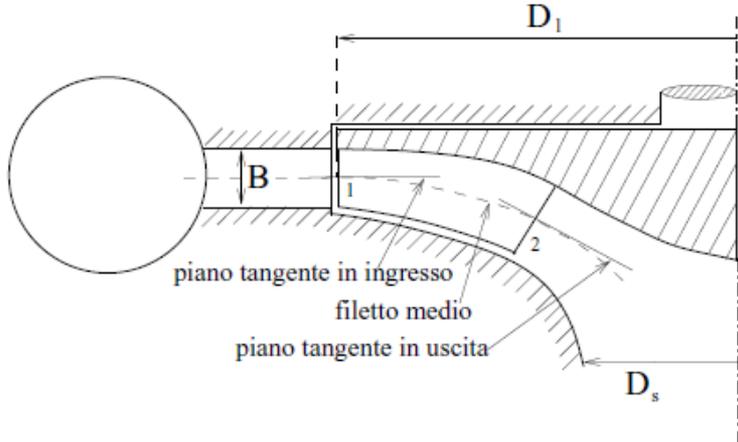
$$\eta_i = \frac{l_i}{g H_u} = \frac{u_1 c_{u1} - u_2 c_{u2}}{g(H_g - H_{cond})}$$

$$\eta_o = \frac{l_o}{l_i} = \frac{P_o}{P_i} = 1 - \frac{P_{md}}{P_i} - \frac{P_{aus}}{P_i}$$

$$\eta_{tot} = \frac{P_o}{\rho Q g H_u} = \eta_o \eta_i$$

$$P_o = \eta_{tot} \rho Q g H_u = \eta_o \rho c_{r1} A_p l_i = \eta_o \rho c_{r1} A_p (u_1 c_{u1} - u_2 c_{u2})$$

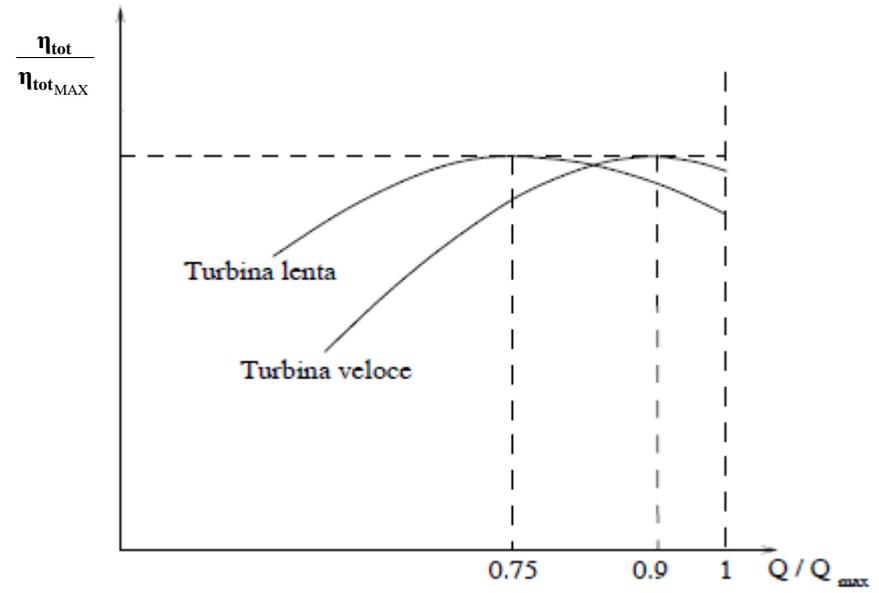
$$\eta_{imp} = \frac{P_o}{\rho Q g H_g} = \frac{P_o}{\rho Q g H_u} \cdot \frac{H_u}{H_g} = \eta_{tot} \eta_{inst}$$

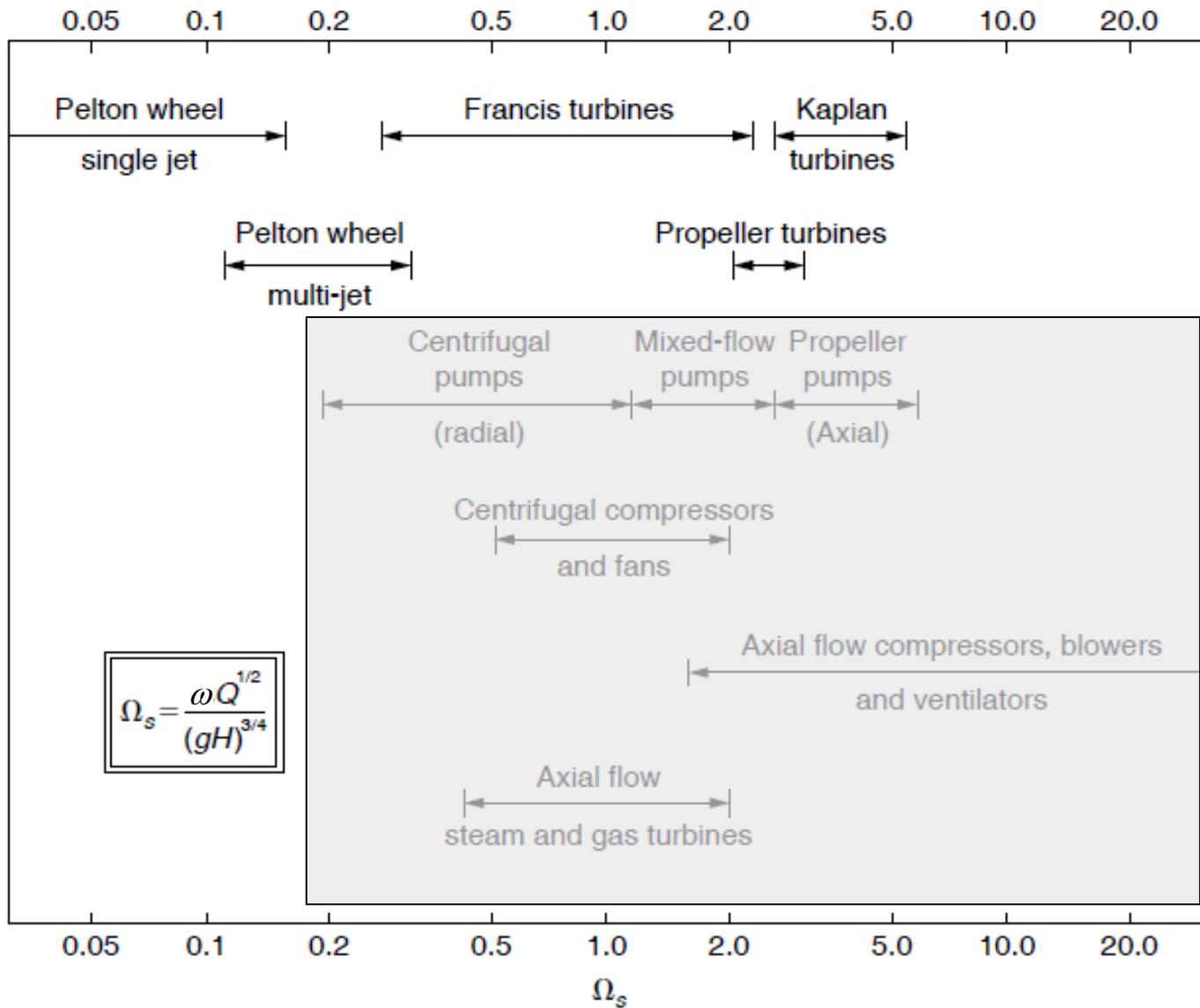


Classe di turbina	$\alpha_1$	$\beta_1$	$\mathcal{R}$	$n_p$
Francis lenta	$15^\circ \div 20^\circ$	$60^\circ \div 70^\circ$	0.3	$60 \div 130$
Francis media	$25^\circ \div 30^\circ$	$90^\circ$	0.4	$\approx 200$
Francis veloce	$35^\circ \div 40^\circ$	$120^\circ \div 130^\circ$	0.5	$350 \div 450$

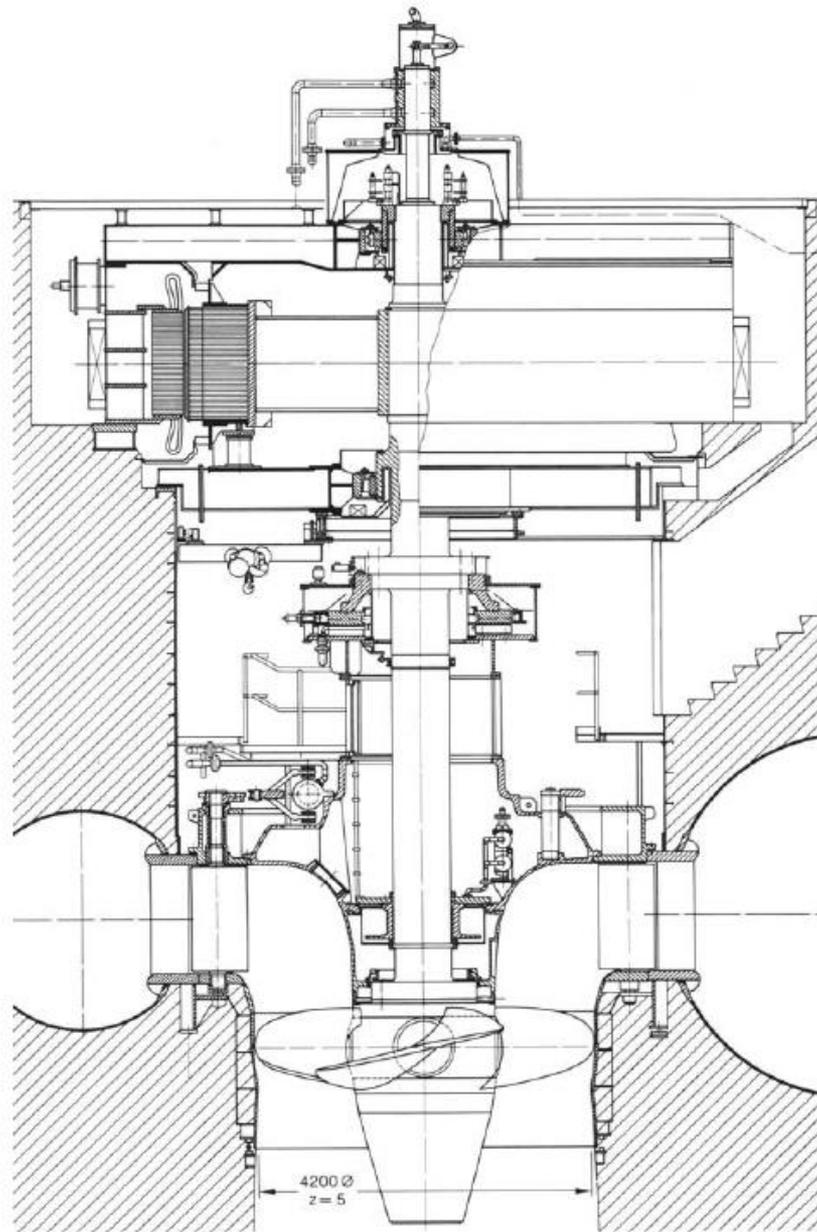
$$n_p = N \frac{P^{\frac{1}{2}}}{H^{\frac{5}{4}}}$$

Tabella 2: Classificazione delle turbine Francis.

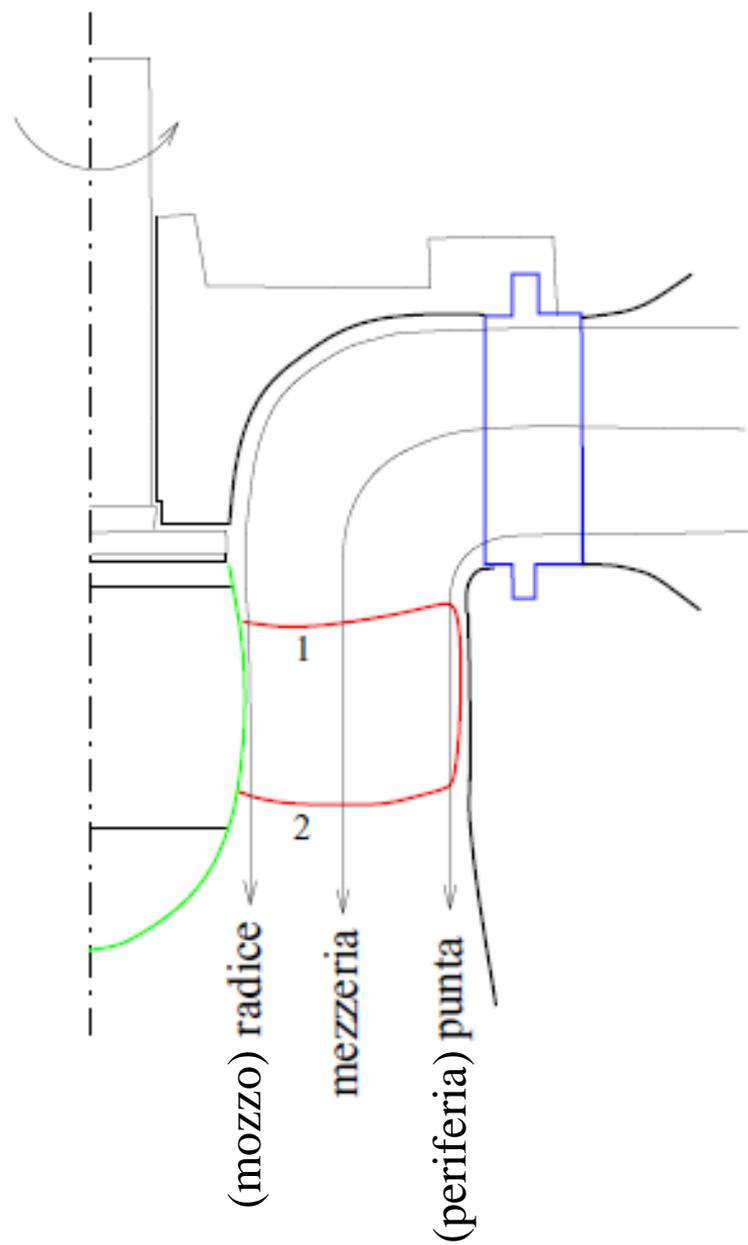
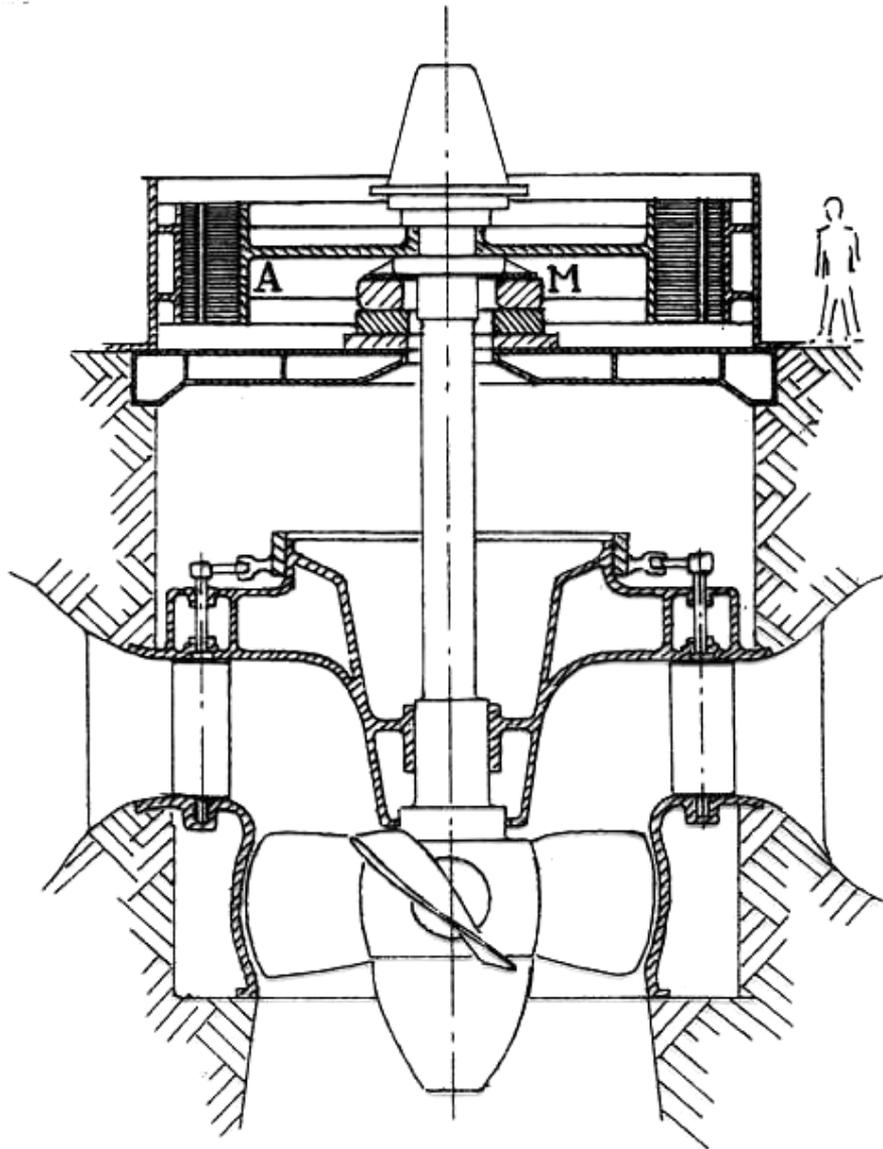


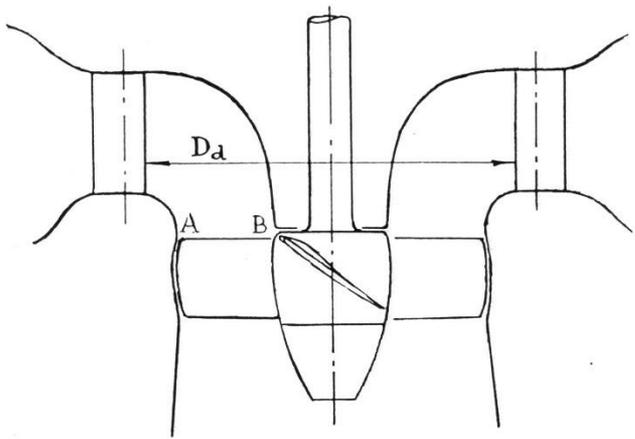


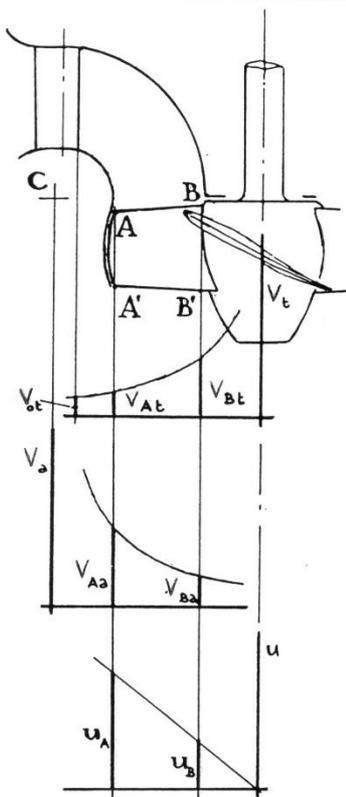
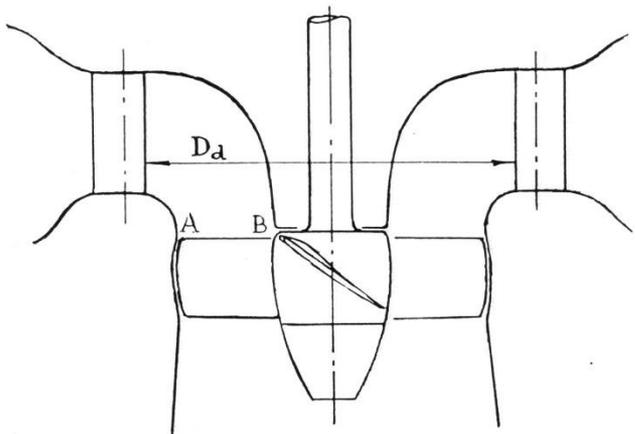
# Turbine ad elica e Kaplan



Sezione di una turbina Kaplan



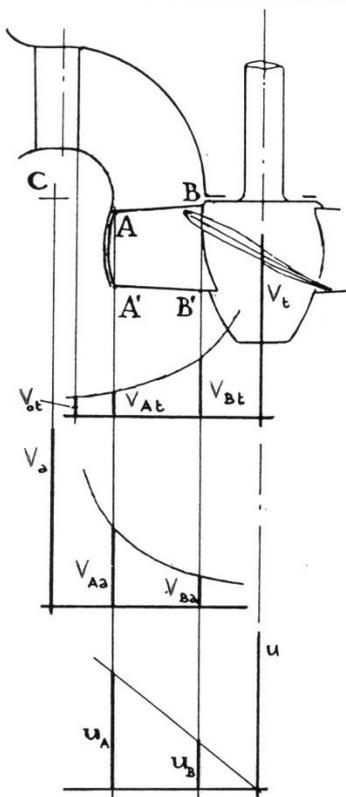
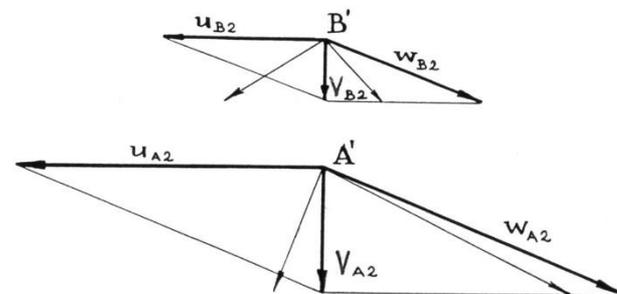
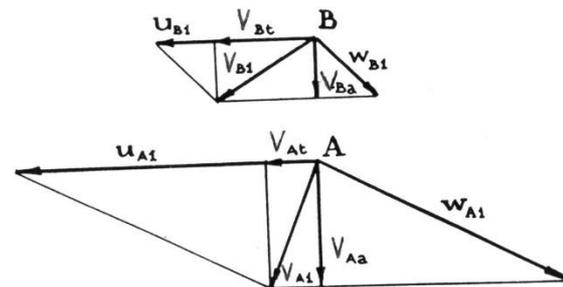
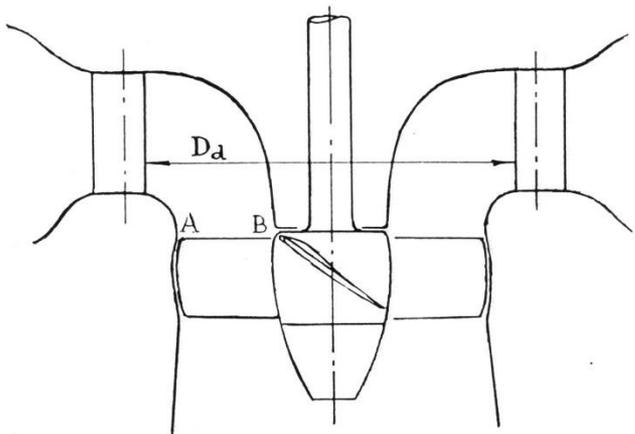




$$V_t r = V_u r = \text{const.} \Rightarrow V_t = V_u = \frac{\text{const.}}{r}$$

$$V_a r_C = \text{const.} \Rightarrow V_a = \frac{\text{const.}}{r_C}$$

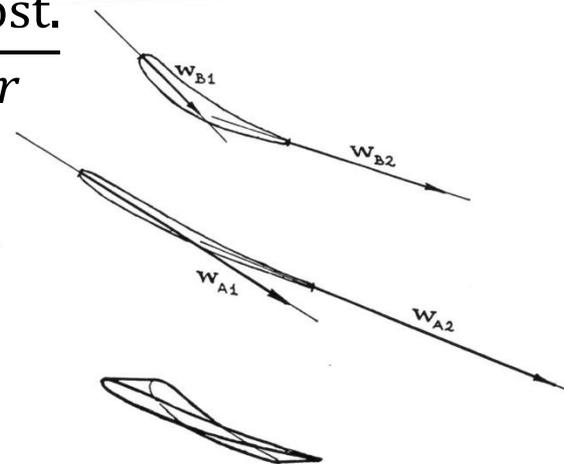
$$u = \omega r \Rightarrow u = \text{const.} \cdot r$$

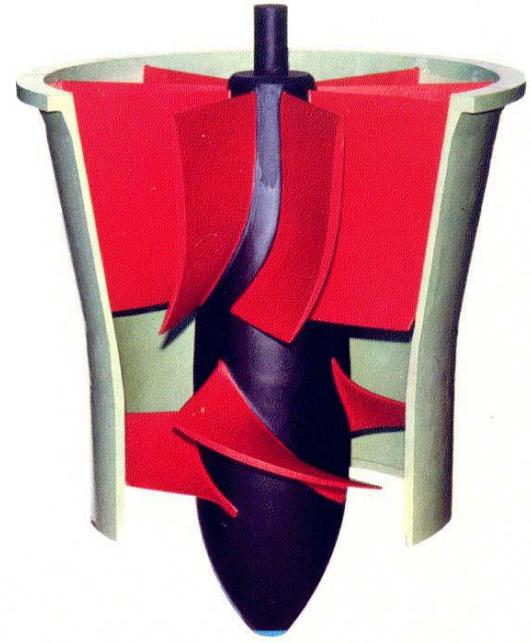
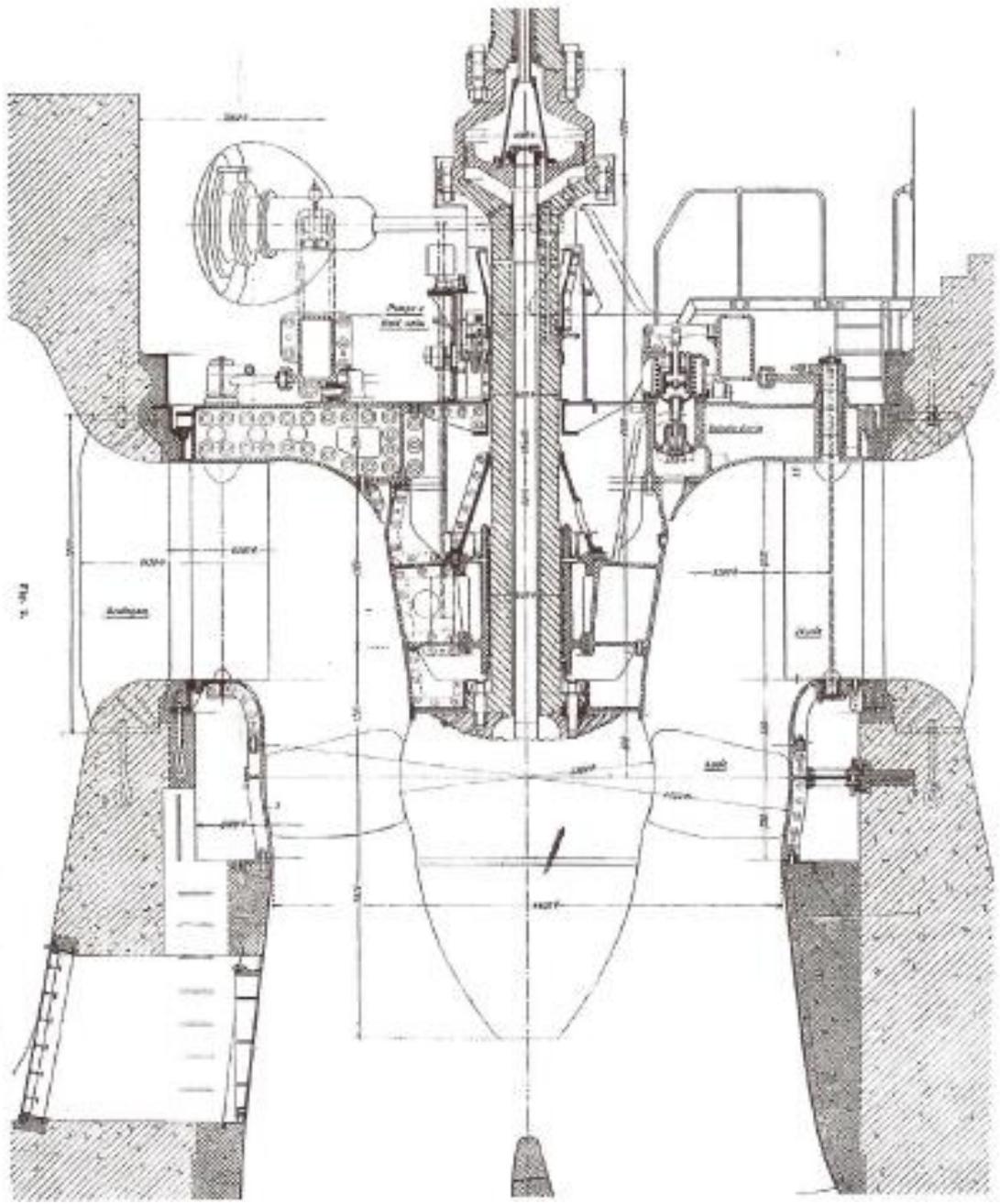


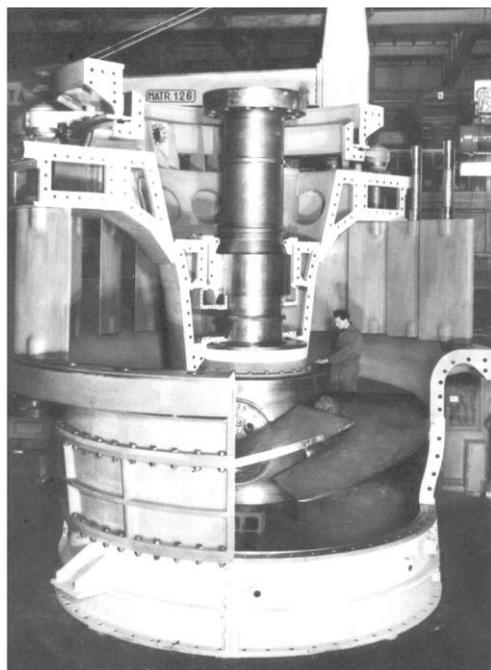
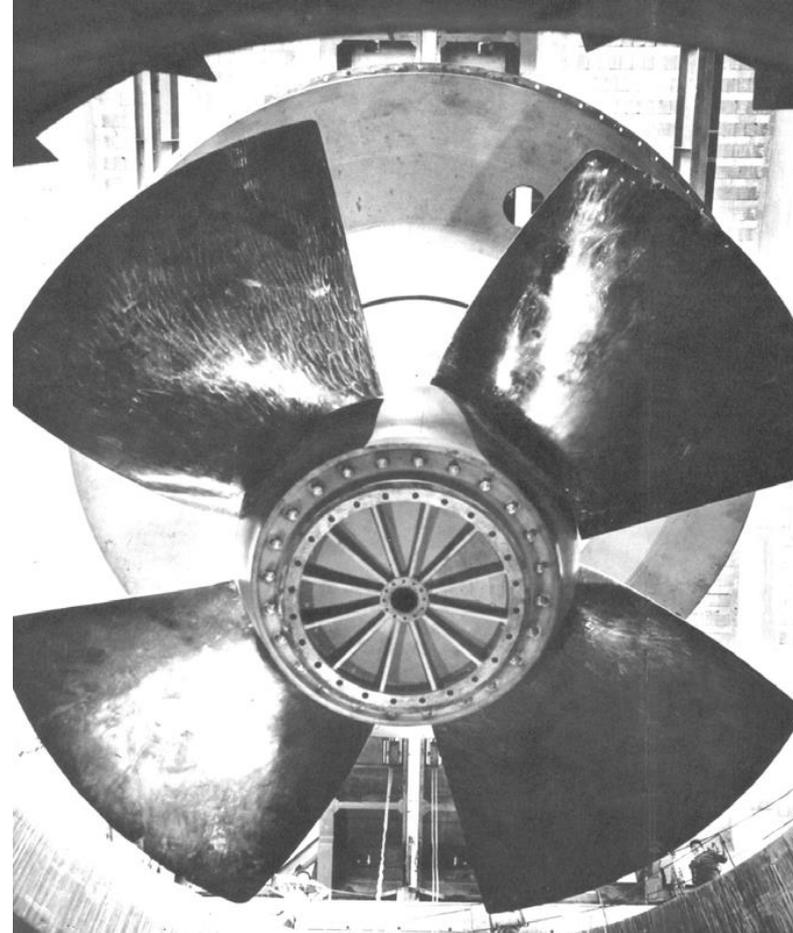
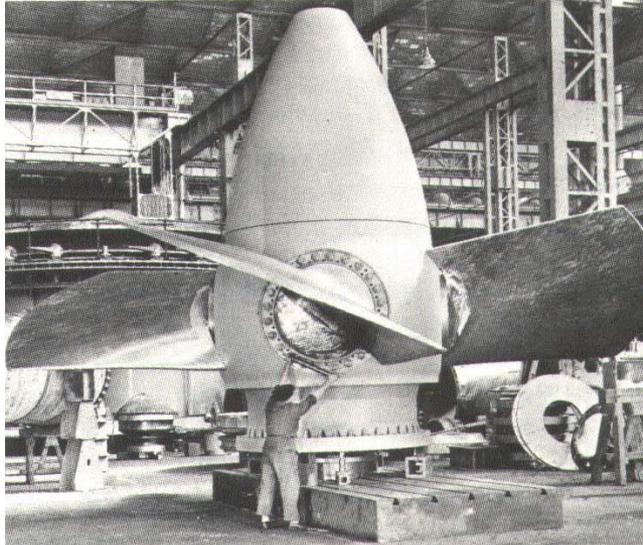
$$V_t r = V_u r = \text{const.} \Rightarrow V_t = V_u = \frac{\text{const.}}{r}$$

$$V_a r_C = \text{const.} \Rightarrow V_a = \frac{\text{const.}}{r_C}$$

$$u = \omega r \Rightarrow u = \text{const.} \cdot r$$







Costruzione: Riva Calzoni

$H = 33.4 \text{ m}$

$Q = 153 \text{ m}^3/\text{s}$

$n = 150 \text{ giri/min}$

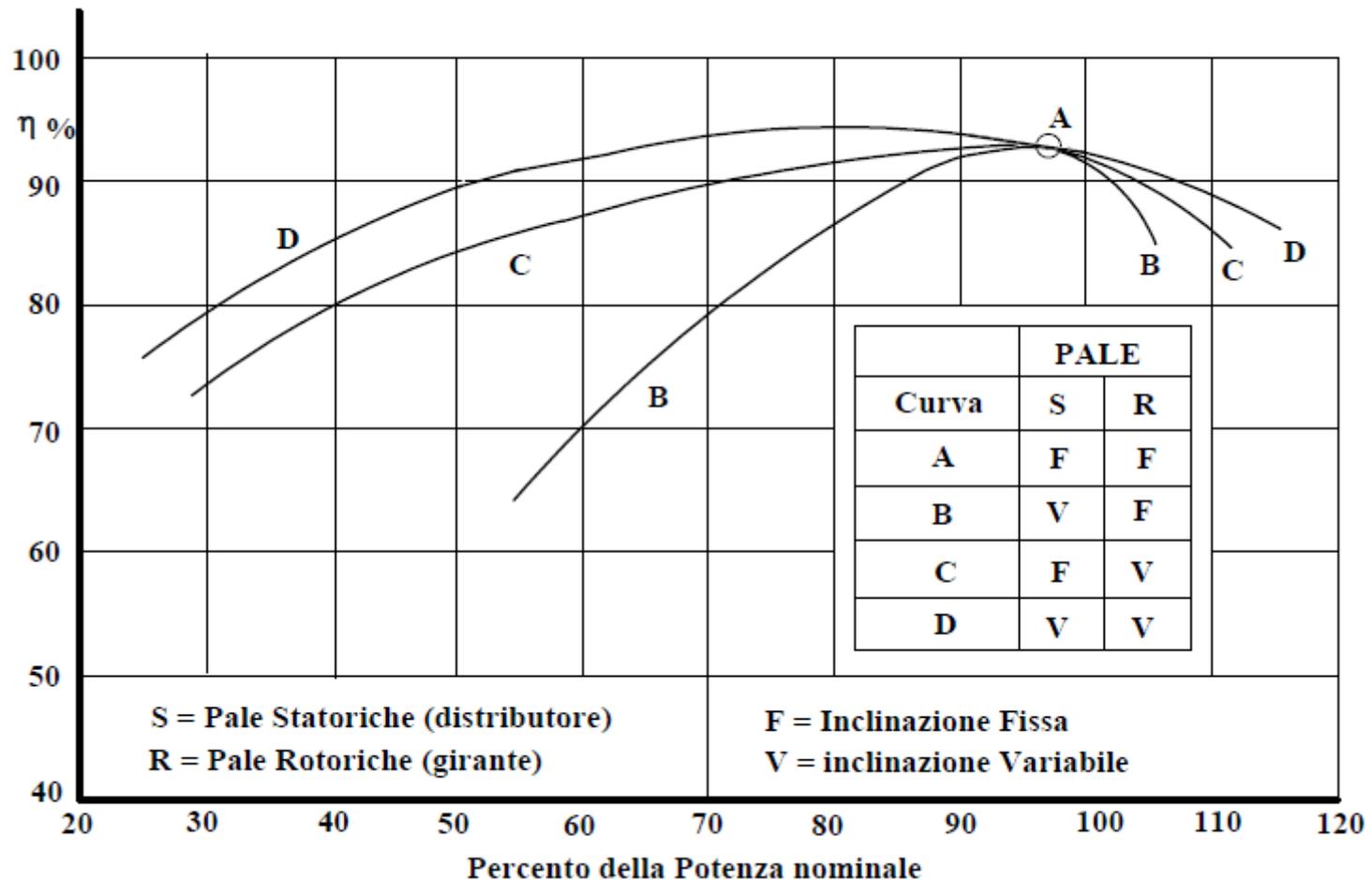
$P = 2 \times 41 \text{ MW}$

Costruzione: Riva

$H = 7.50-4.25 \text{ m}$

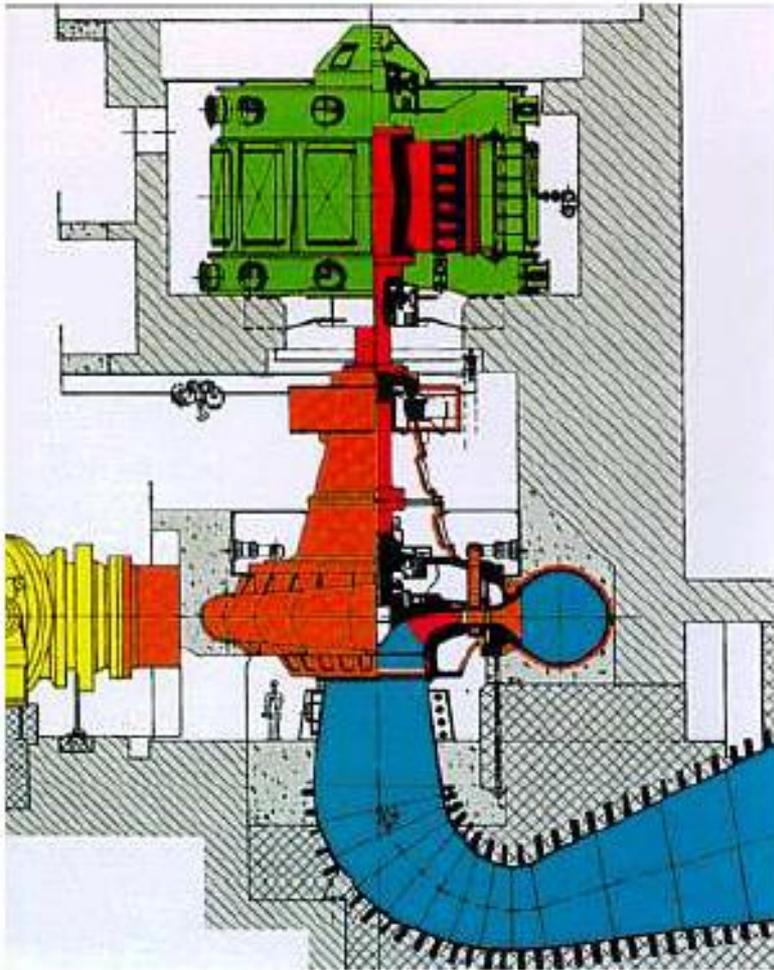
$Q = 185-300 \text{ m}^3/\text{s}$

$n = 53.57 \text{ giri/min}$

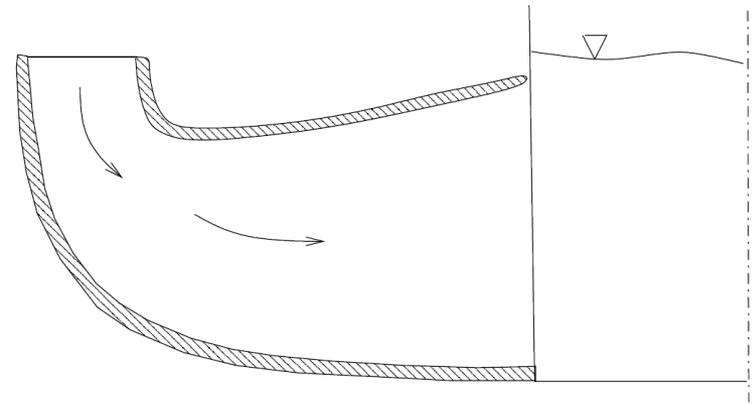
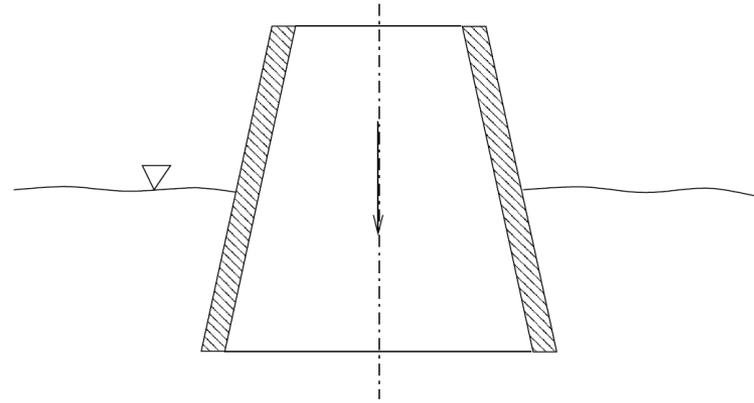
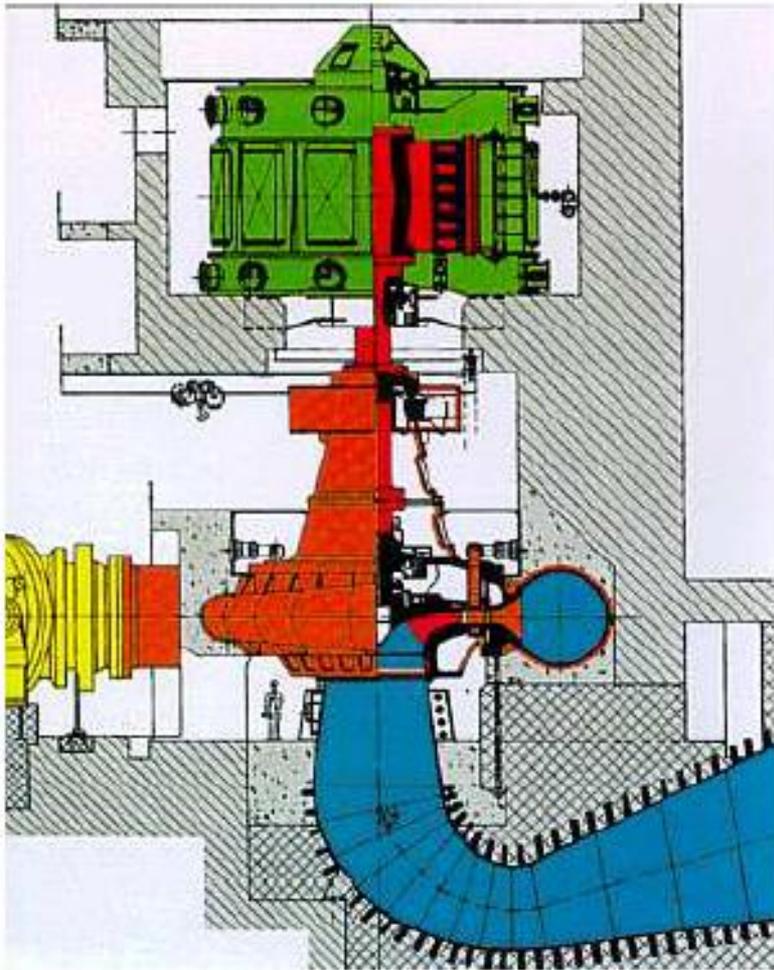


Andamento del rendimento nelle varie condizioni di regolazione delle pale.

# Recupero dell'energia allo scarico della turbina

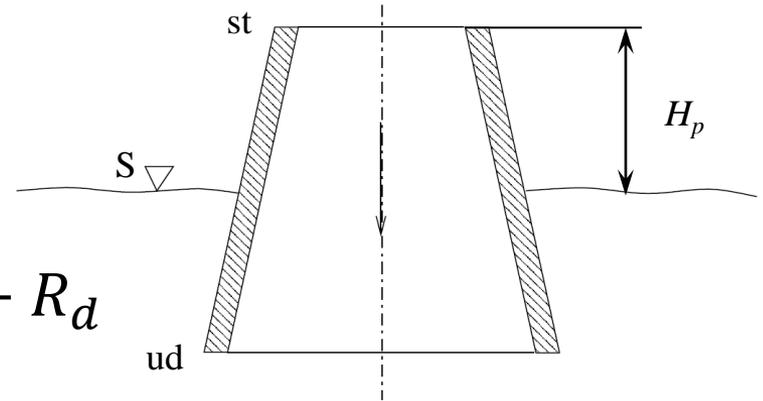


# Recupero dell'energia allo scarico della turbina



# Recupero dell'energia allo scarico della turbina

$$\frac{V_{st}^2}{2} + \frac{p_{st}}{\rho} + gz_{st} = \frac{V_{ud}^2}{2} + \frac{p_{ud}}{\rho} + gz_{ud} + R_d$$

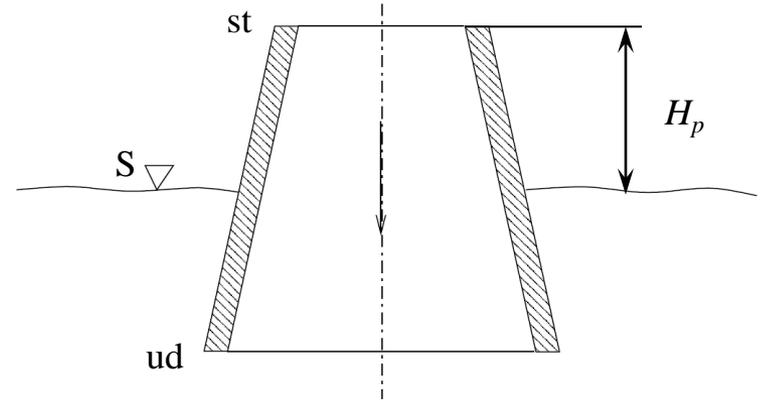


$$\frac{p_{ud}}{\rho} = \frac{p_S}{\rho} + g(z_S - z_{ud})$$

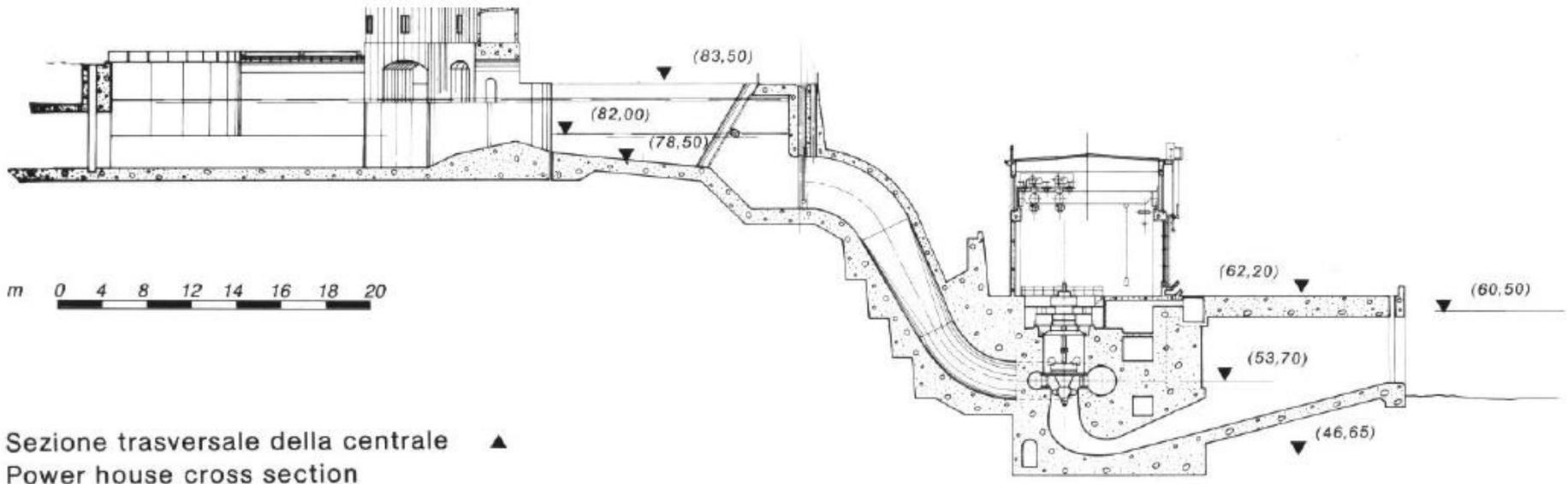
$$\begin{aligned} \frac{p_{st}}{\rho} &= \frac{p_S}{\rho} - g(z_{st} - z_S) - \frac{V_{st}^2 - V_{ud}^2}{2} + R_d = \\ &= \frac{p_S}{\rho} - gH_p - \frac{V_{st}^2 - V_{ud}^2}{2} + R_d \end{aligned}$$

# Indice di Thoma

$$\frac{p_{st}}{\rho} = \frac{p_s}{\rho} - gH_p - \frac{V_{st}^2 - V_{ud}^2}{2} + R_d$$



$$\sigma = \frac{NPSH}{H} = \frac{\frac{p_{st} - p_v}{\rho g} + \frac{V_{st}^2}{2g}}{H} \approx \frac{\frac{p_s - p_v}{\rho g} - H_p}{H}$$



Turbina Kaplan sotto battente, con tubo diffusore a gomito