HYDRO AND EOLIC PLANTS

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EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

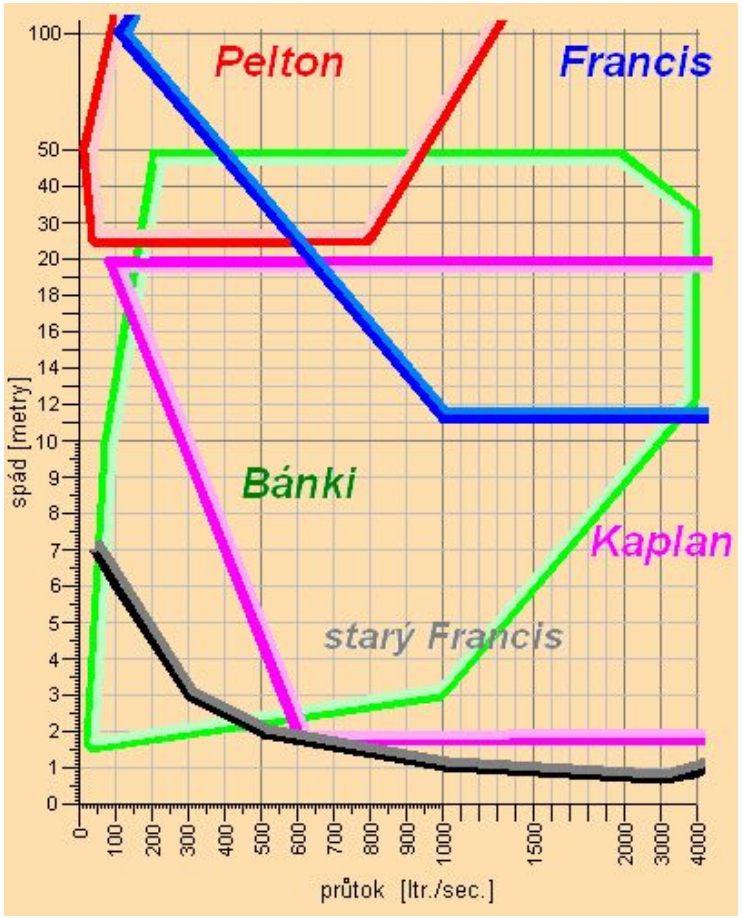


Hydraulic engines 3

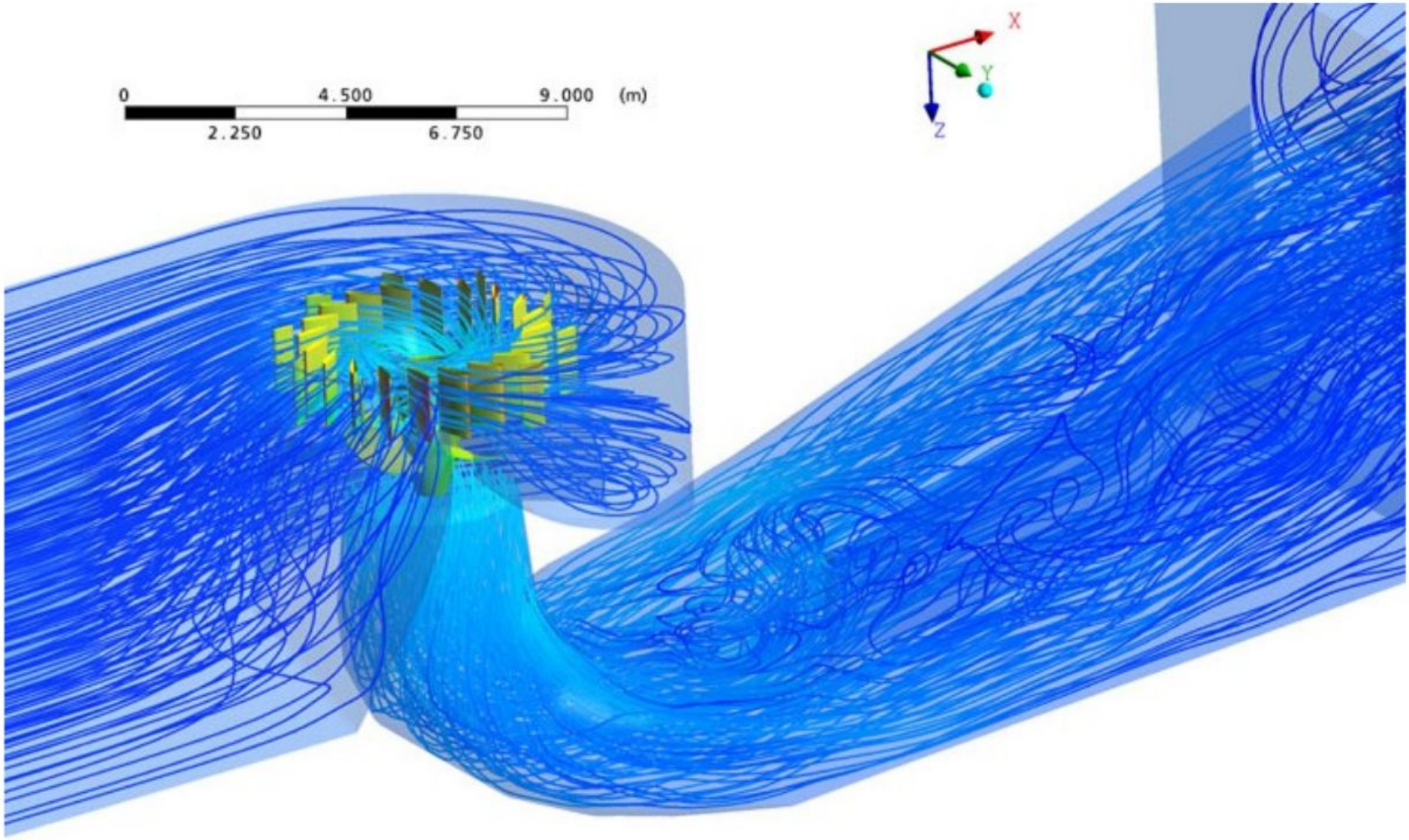
Milan Bělík

Hydraulic turbines

- **Action turbines**
  - Pelton turbin
  - Reiffenstein turbine
  - Sfindex turbine
  - Swift turbine
  - Segner turbine
  - Zuppinger turbine
  - Turgo turbine
  - Girard turbine
  - Hänel turbine
  - Schwamkrug turbine
  - Bánki turbine
- **Reaction turbines**
  - Kaplan
  - Thoman
  - propeler
  - Francis
  - Fourneyron
  - Jonval
  - Henschel-Jonval
  - Francis-Reiffenstein
  - Dériaz

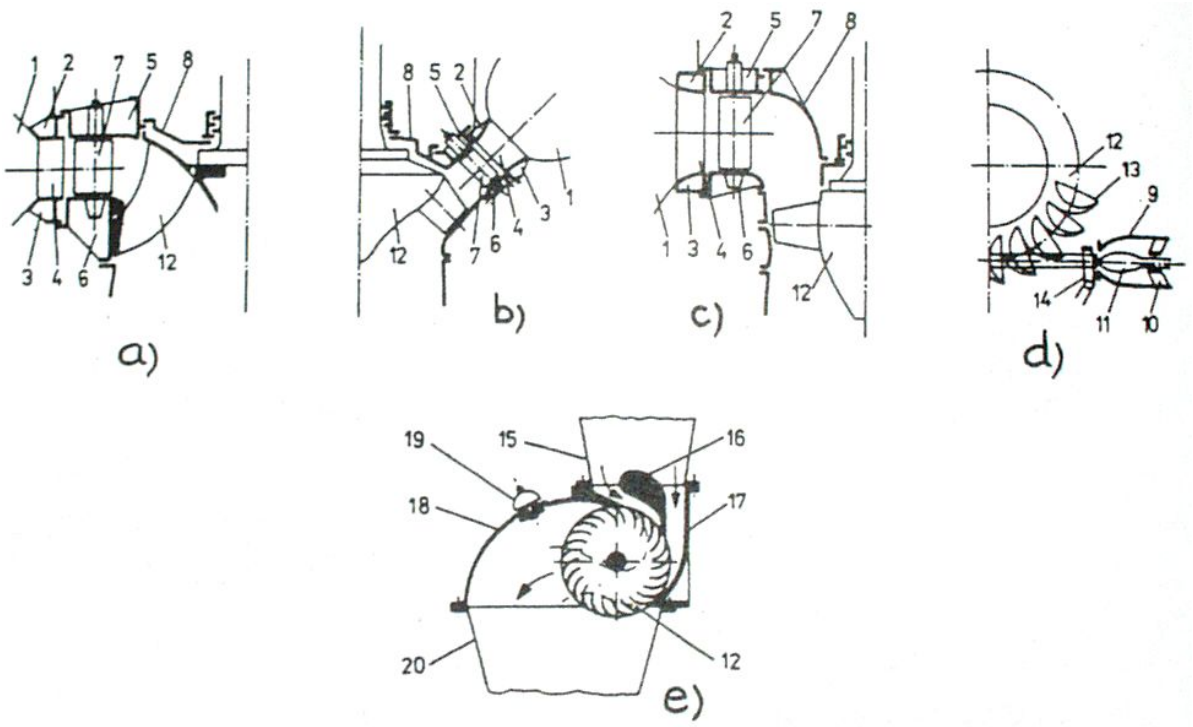


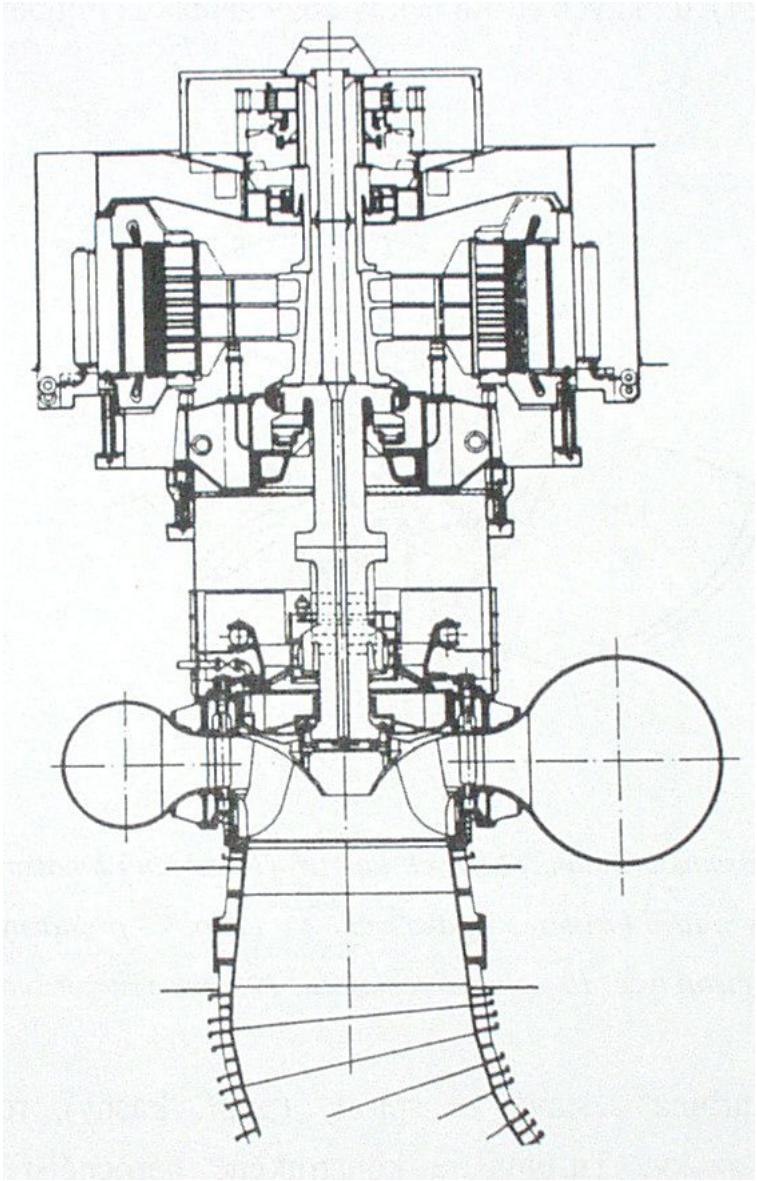


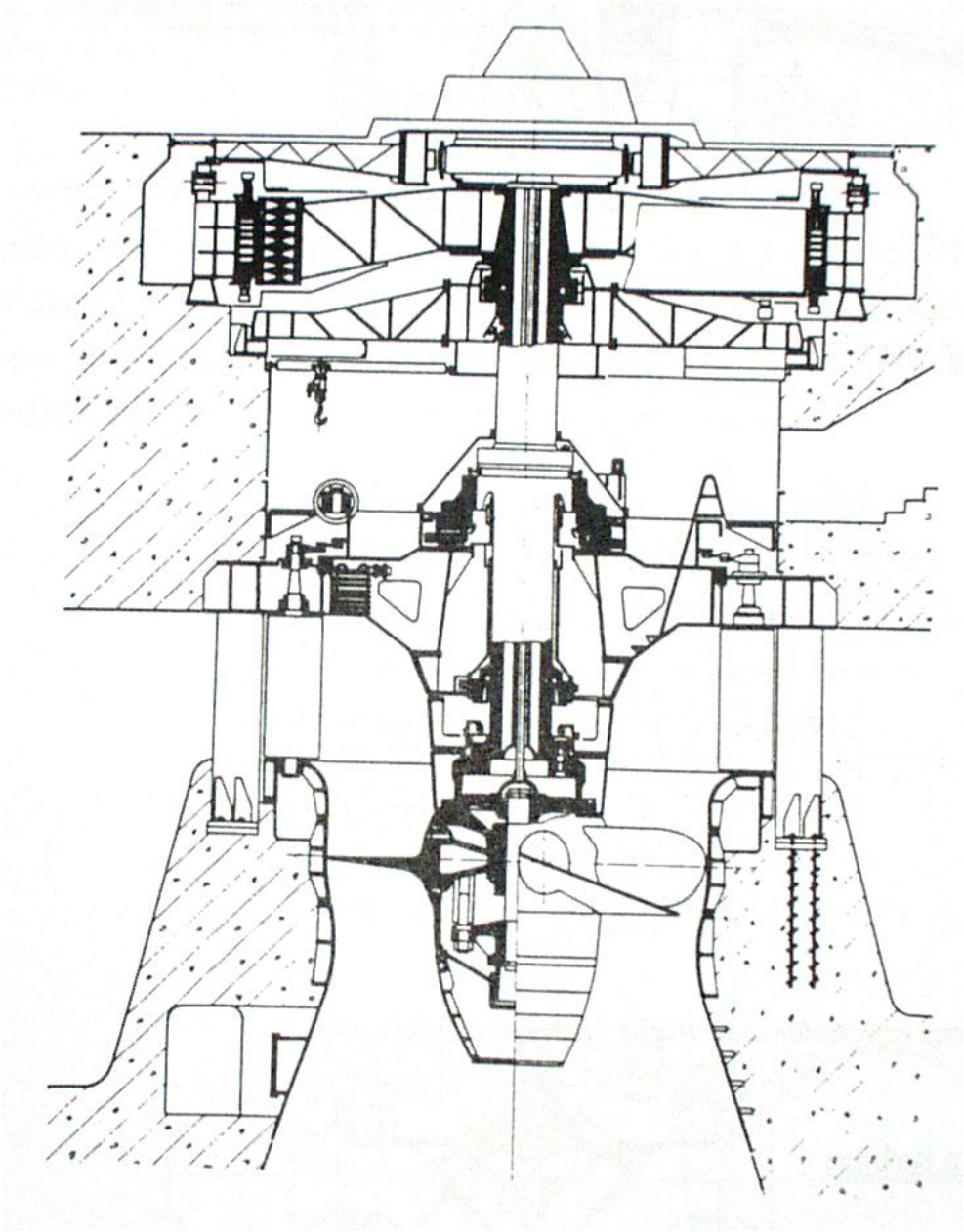

0
4.500
9.000
(m)
2.250
6.750
X
Y
Z

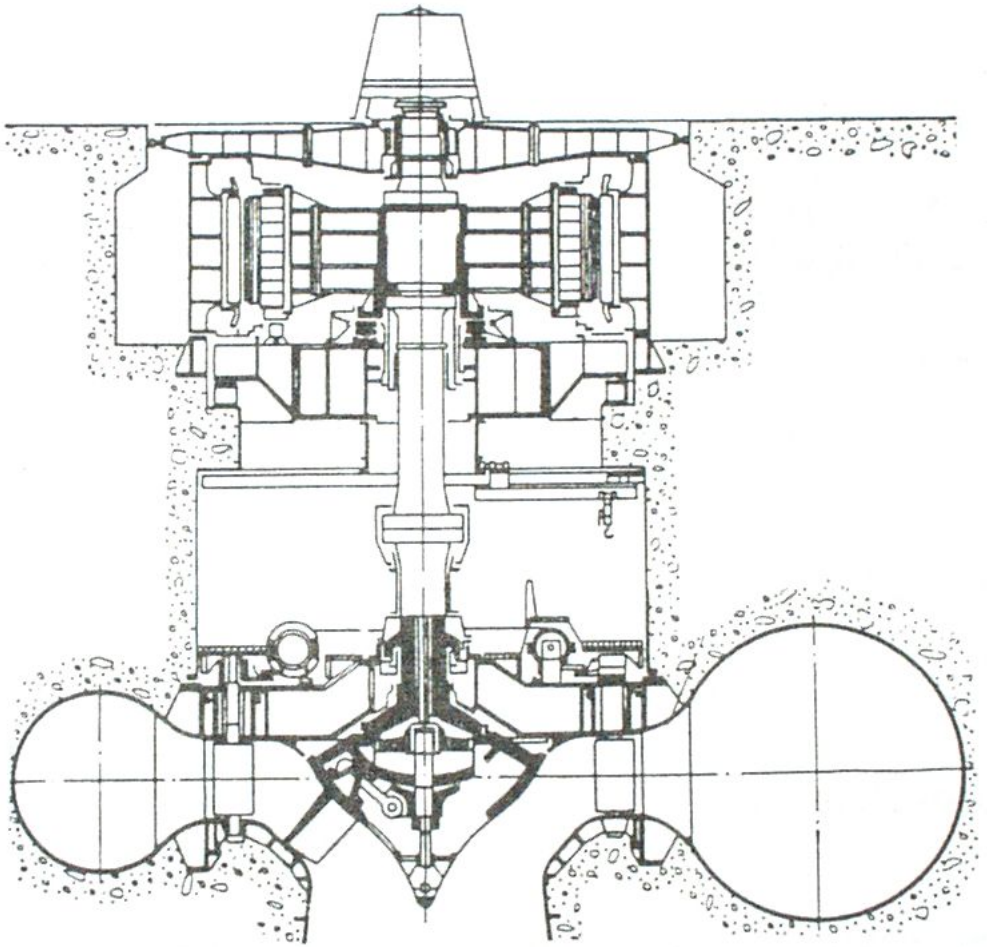
Most utilized turbines

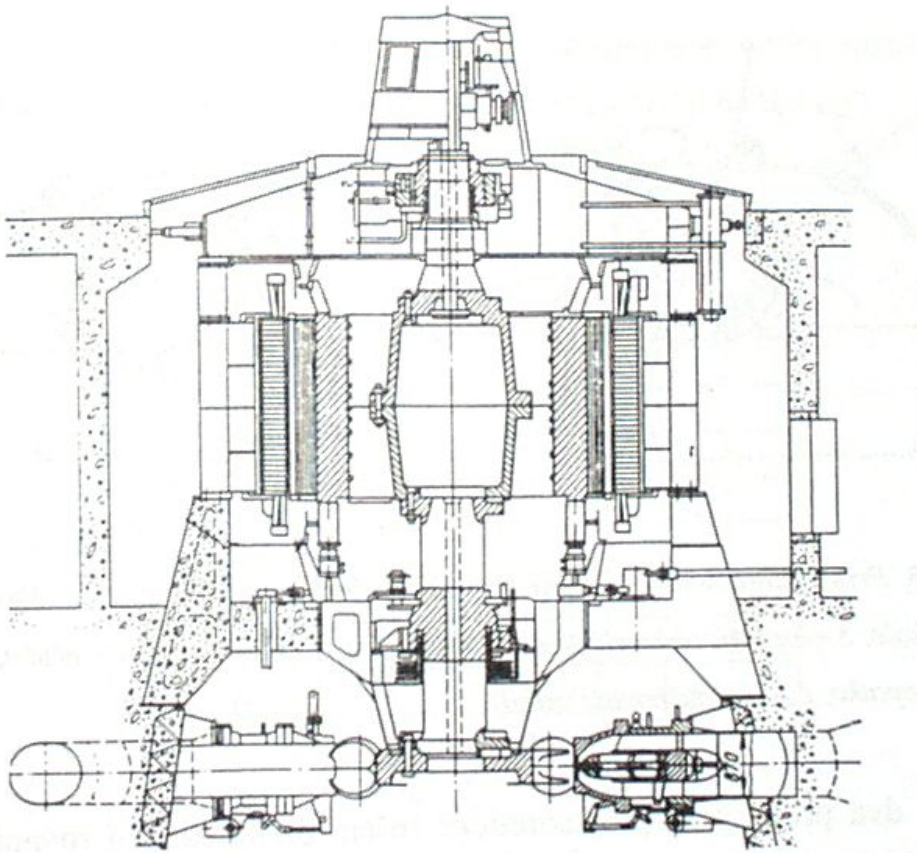
- Francis
- Dériaz
- Kaplan
- Pelton
- Bánki

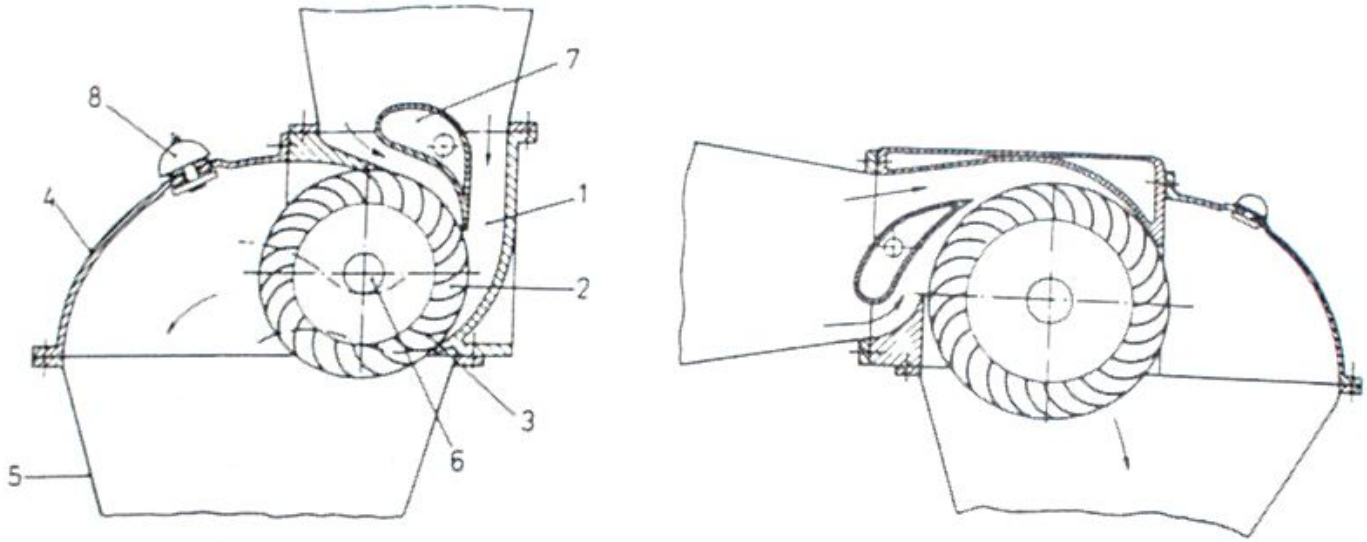











8
7
4
1
2
3
6
5

Main parameters of turbine

- **flow Q [m^3/s]**
- **energy E [J/kg]**
- **Bernouli equation**

$$E = g * H$$

$$E = E_z + E_p + E_v$$

$$E = g \cdot z + \frac{p}{\rho} + \frac{v^2}{2}$$

$E_1 = E_2 = konst$ $E_1 > E_2$

Turbine energy

$$\eta = \eta_Q \cdot \eta_h \cdot \eta_m$$

$$\eta_Q = \frac{Q - Q_z}{Q} = 1 - \frac{Q_z}{Q}$$

$$\eta_h = \frac{P_h}{P_t} = \frac{E - E_z}{E}$$

$$\eta = \frac{P}{P_h} = \frac{P_h - P_z}{P_h} = 1 - \frac{P_z}{P_h}$$

- **Dynamics of a liquid**

$$a = dc/dt$$

$$F = m \cdot dc/dt = m.a$$

$$m = \rho.V$$

$$F = m/dt \cdot dc$$

$$m/dt = \rho.V/dt = \rho.Q$$

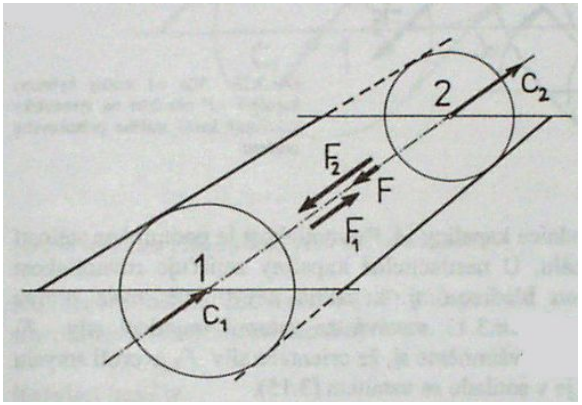
$$F = \rho.Q.\Delta c = \rho.Q.(c_1 - c_2) = F_1 - F_2$$

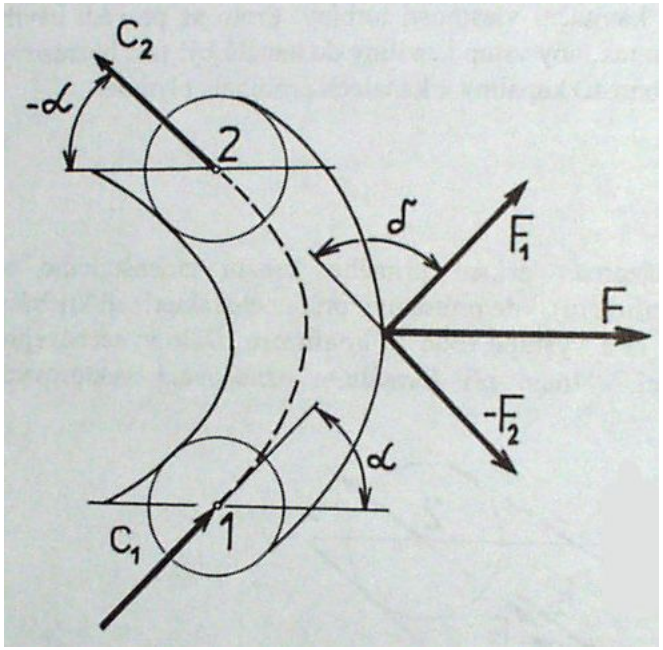
$$E_A - E_B = g \cdot (z_A - z_B) + \frac{p_A - p_B}{\rho} + \frac{v_A^2 - v_B^2}{2}$$

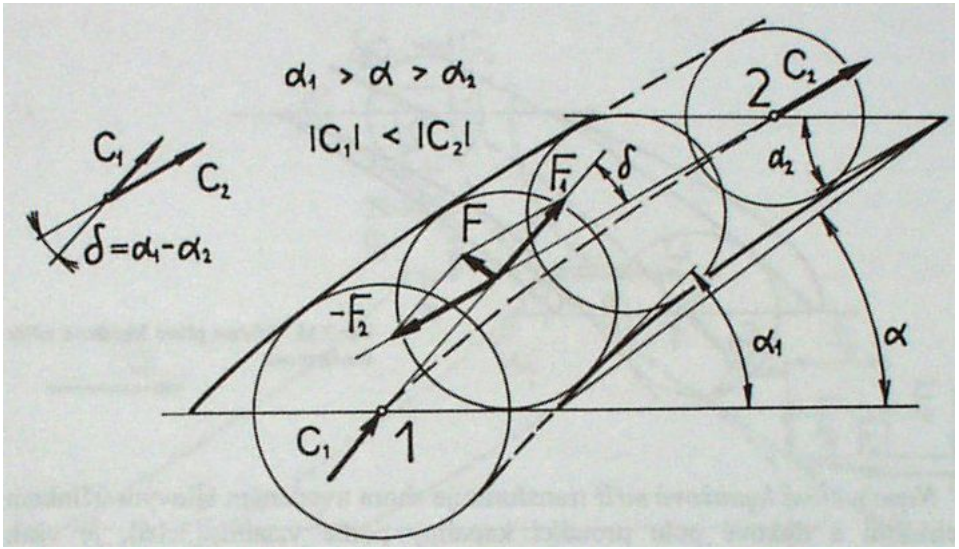
$$E = g \cdot (z_1 - z_2) + \frac{p_1 - p_2}{\rho} + \frac{v_1^2 - v_2^2}{2}$$

$$E = g \cdot (z_A - z_B) + \frac{p_A - p_B}{\rho} + \frac{v_A^2 - v_B^2}{2} - E_d$$

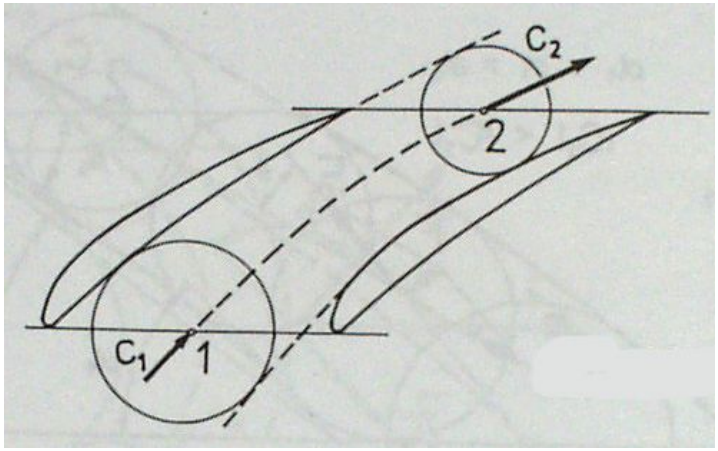
$$0{,}5.\Delta c^2 + \Delta p.\rho^{-1} = 0{,}5.(c_1^2 - c_2^2) + (p_1 - p_2).\rho^{-1} = 0$$

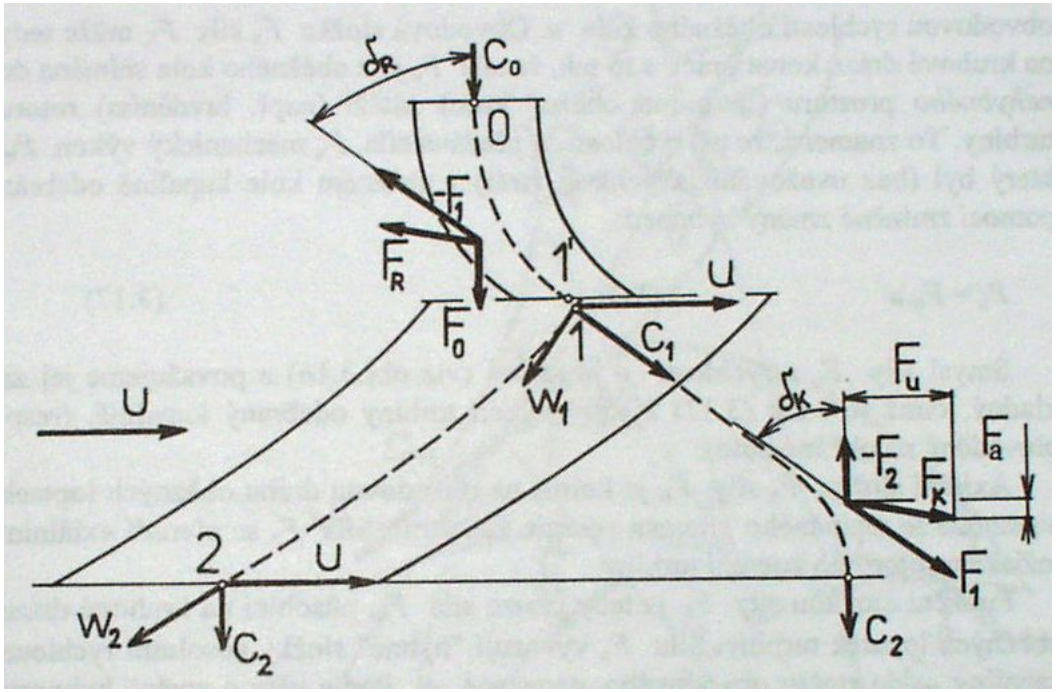




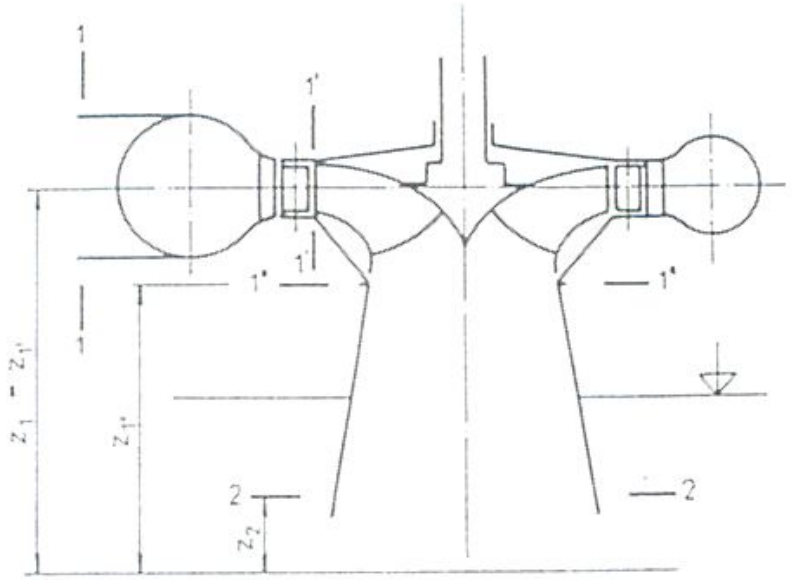


- **blade grid**





Action turbines



$$E_1 = z_1 \cdot g + \frac{p_1}{\rho} + \frac{v_1^2}{2}$$

$$E_{1'} = z_{1'} \cdot g + \frac{p_{1'}}{\rho} + \frac{v_{1'}^2}{2}$$

$$E_{1''} = z_{1''} \cdot g + \frac{p_{1''}}{\rho} + \frac{v_{1''}^2}{2}$$

$$E_2 = z_2 \cdot g + \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

$$E_1 = E_{1'} + E_{d(1-1')}$$

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_{1'}}{\rho} + \frac{v_{1'}^2}{2} + E_{d(1-1')}$$

$$p_1 > p_{1'} > p_2$$

$$E = g \cdot (z_1 - z_2) + \frac{p_1 - p_2}{\rho} + \frac{v_1^2 - v_2^2}{2}$$

$$F_R.r_R = F_K.r_K$$

$$F_K.r_K = F_{u1}.r_1 - F_{u2}.r_2$$

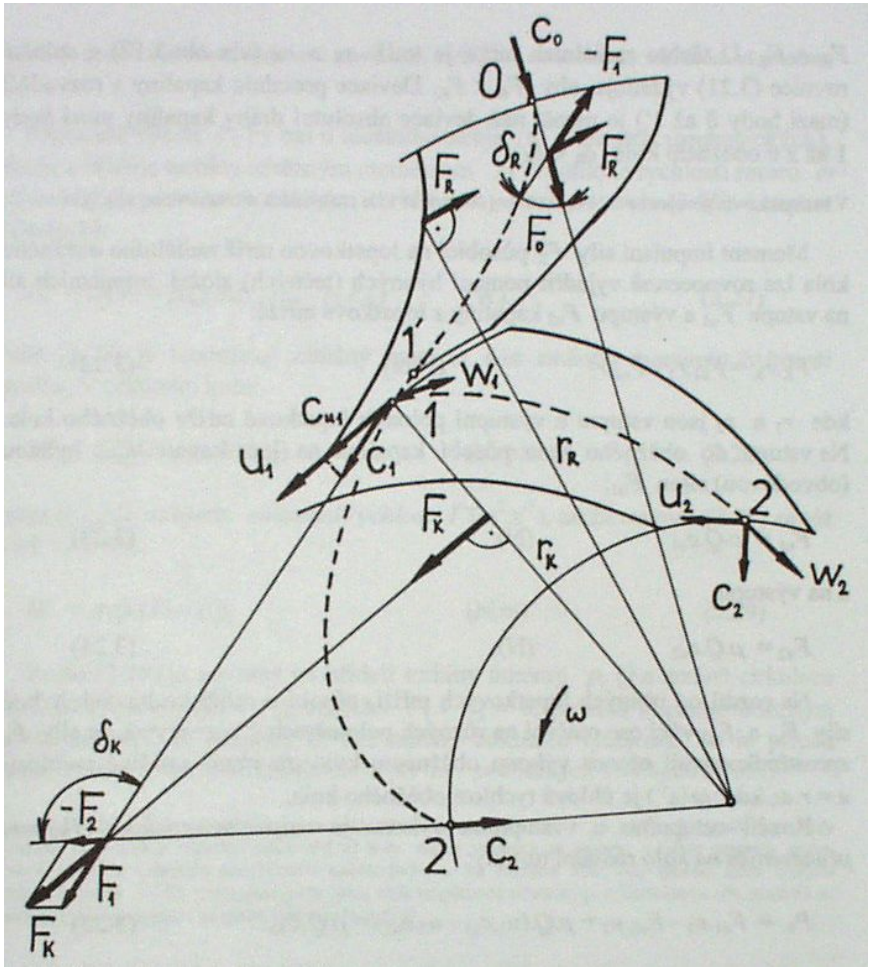
$$F_{u1} = \rho.Q.c_{u1}$$

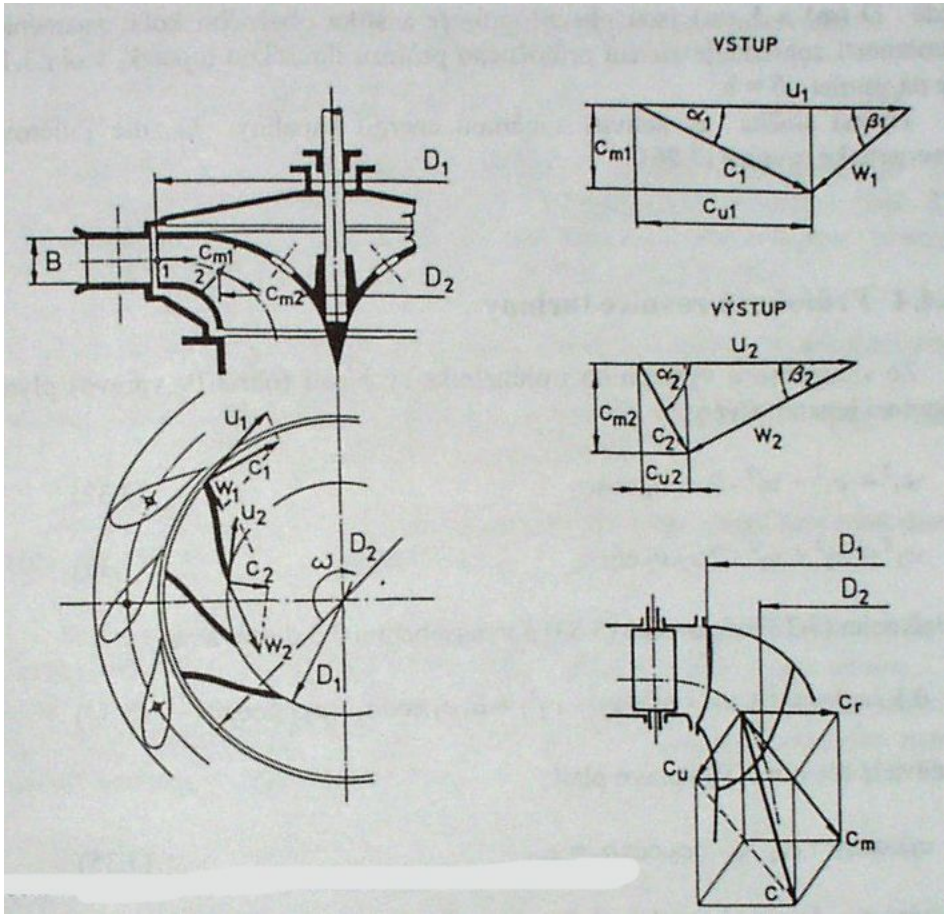
$$F_{u2} = \rho.Q.c_{u2}$$

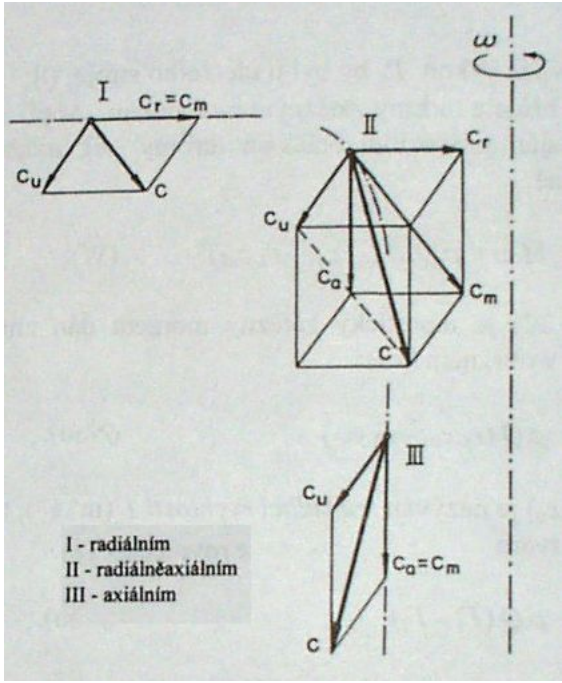
$$P_h = F_{u1}.u_1 - F_{u2}.u_2 = \rho.Q.(u_1.c_{u1} - u_2.c_{u2}) = \rho.Q.E_{Kt}$$

$$P_h = M.\omega = \rho.Q.\omega.(r_1.c_{u1} - r_2.c_{u2})$$

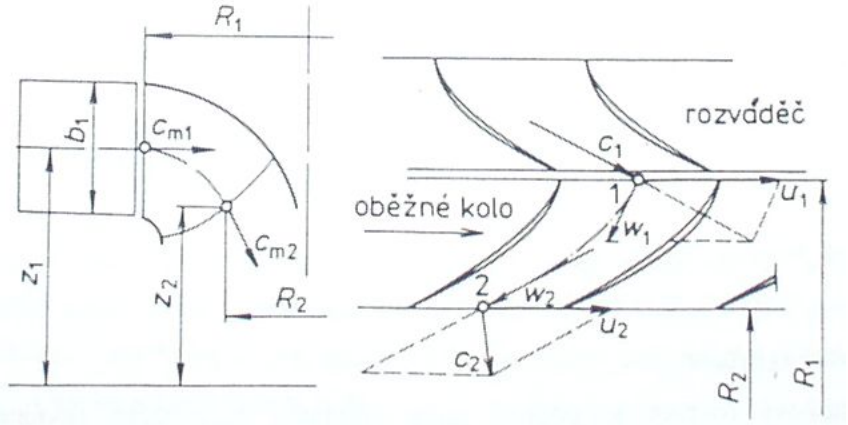
$$M = \rho.Q.(\Gamma_1 - \Gamma_2)$$




VSTUP
U_1
α_1
β_1
c_{m1}
c_1
w_1
c_{u1}
D_1
D_2
B
1
2
c_{m1}
c_{m2}
VÝSTUP
U_2
α_2
β_2
c_{m2}
c_2
w_2
c_{u2}
U_1
c_1
w_1
U_2
c_2
w_2
ω
D_2
D_1
D_1
D_2
c_r
c_u
c_m
c

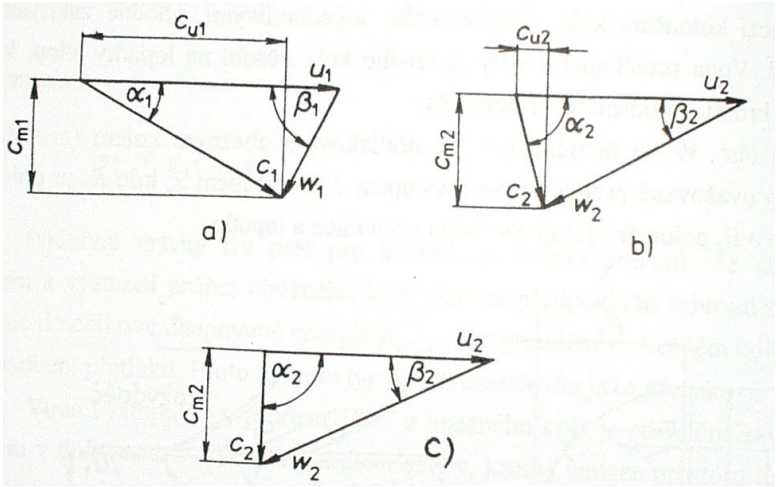

ω
I
$c_r = c_m$
c_u
c
II
c_r
c_u
c_a
c_m
c
III
c_u
$c_a = c_m$
c
I - radiálním
II - radiálněaxiálním
III - axiálním

Euler equation



$$E \cdot \eta_h = u_1 \, c_{u1} - u_2 \, c_{u2}$$

$$Q_k = 2\pi R_1 \, b_1 \, c_{m1}$$



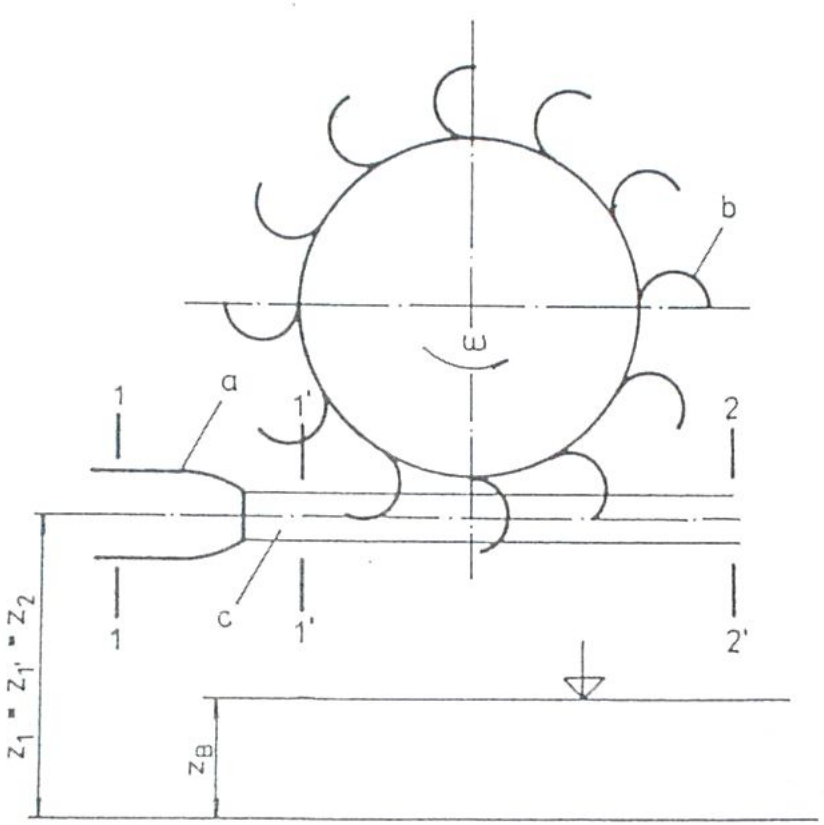
$$w_1^2 = c_1^2 + u_1^2 - 2\,u_1\,c_1\cos\alpha_1 \qquad c_1\cos\alpha_1 = c_{u1}$$

$$w_2^2 = c_2^2 + u_2^2 - 2\,u_2\,c_2\cos\alpha_2 \qquad c_2\cos\alpha_2 = c_{u2}$$

$$u_1\,c_{u1} - u_2\,c_{u2} = \frac{1}{2}\left(w_2^2 - c_2^2 - u_2^2 - w_1^2 + c_1^2 + u_1^2\right)$$

$$E \cdot \eta_h = \frac{c_1^2 - c_2^2}{2} + \frac{w_2^2 - w_1^2}{2} + \frac{u_1^2 - u_2^2}{2}$$

Reaction turbines



$$E_1 = \frac{p_1}{\rho} + \frac{v_1^2}{2}$$

$$E_{1'} = \frac{p_{1'}}{\rho} + \frac{v_{1'}^2}{2}$$

$$E_2 = \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

$$E_1 = E_{1'} + E_{d(1-1')} = E_2 + E_{d(1-2)}$$

$$p_1 = p_{1''} + p_b$$

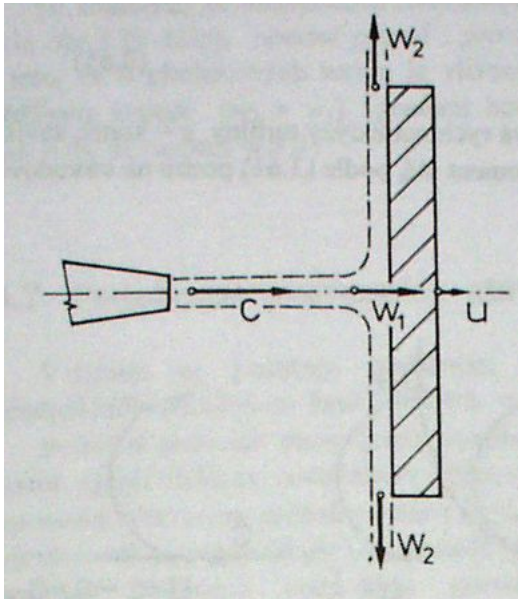
$$p_{1'} = p_2 = p_b$$

$$\frac{p_{1''}}{\rho} + \frac{v_1^2}{2} = \frac{v_{1'}^2}{2} + E_{d(1-1')} = \frac{v_2^2}{2} + E_{d(1-2)}$$

$$E = \frac{p_{1''}}{\rho} + \frac{v_1^2 - v_2^2}{2}$$

$$E = 0{,}5.c^2$$

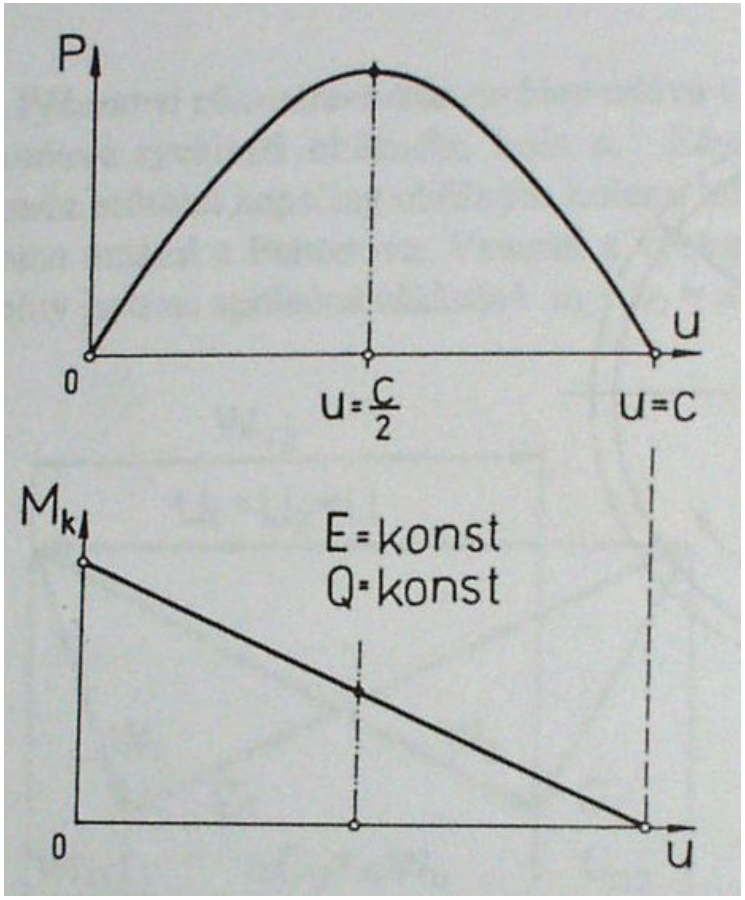
$$P = \rho.Q.u.\Delta w_u$$

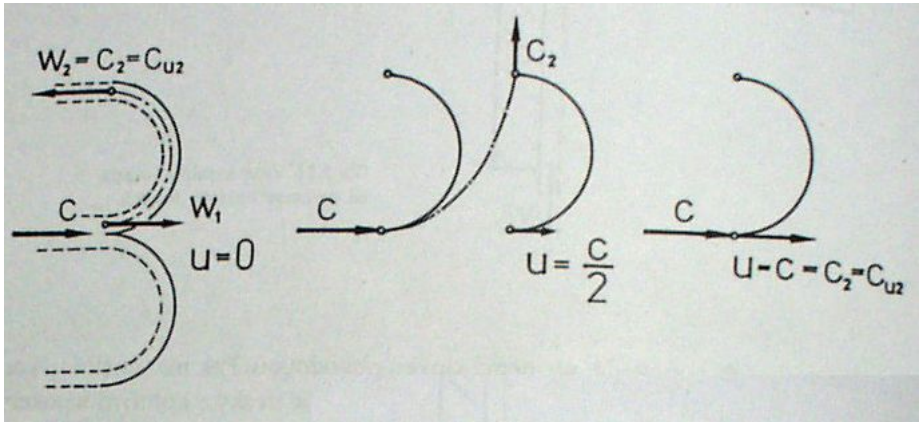


$$P_{max} = \rho.Q.u.w_1 = \rho.Q.u.(c - u) = \rho.Q.0{,}5.c.(c - 0{,}5.c) = \rho.Q.0{,}25.c^2$$

$$\eta_h = 0{,}25.c^2.(0{,}5.c^2)^{-1} = 0{,}5$$

$$M_k = \rho.Q.(r_1.c_{u1} - r_2.c_{u2})$$





1) $u = 0$; $c_{u2} = - c$

2) $u = 0{,}5.c$; $c_{u2} = 0$

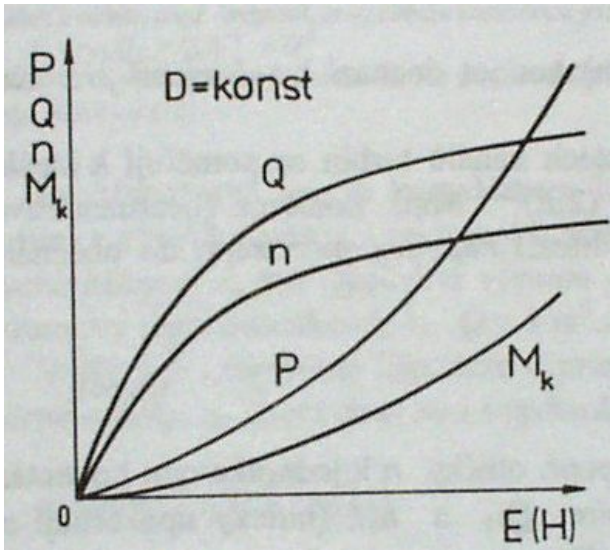
3) $u = c$; $c_{u2} = c$

1) $M_k \sim (c - c_{u2}) = [c - (-c)] = 2.c$

2) $M_k \sim (c - c_{u2}) = c$

3) $M_k \sim (c - c_{u2}) = 0$.

Operation similarity



$$c_1^* = c_1.(2.E)^{-0,5}$$

$$E.E'^{-1} = (u.u'^{-1})^2 = [D.n.(D'.n')^{-1}]^2 = (D.n.n_{11}^{-1})^2$$

$$n_{11} = D.n.E^{-0,5}$$

$$Q.Q' = (D.D'^{-1})^3 \,.\, n.n'^{-1} = Q.Q_{11}^{-1} = D^3 \,.\, n.n_{11}^{-1}$$

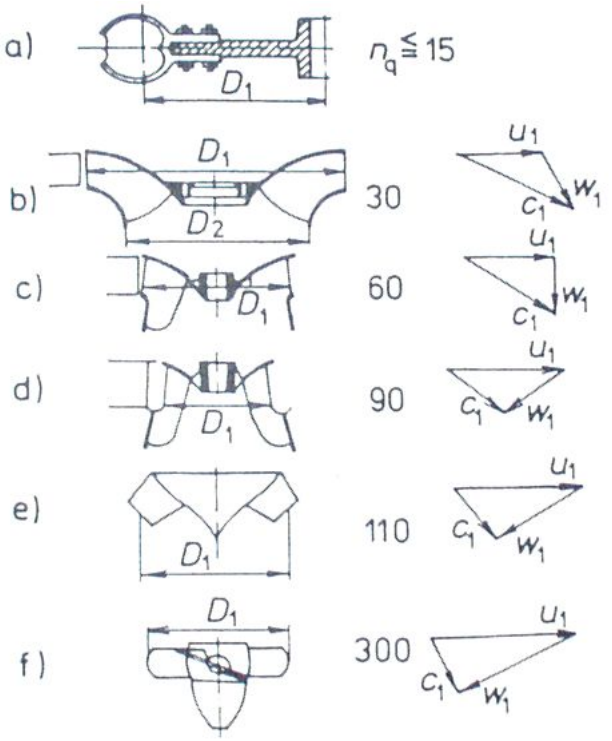
$$Q_{11} = Q.n_{11} \,.\, (D^3.n)^{-1} = Q.(D^2.E^{0,5})^{-1}$$

$$n_b = n_{11}.Q_{11}^{0,5} = n.D.E^{-0,5} \,.\, [Q.(D^2.E^{0,5})^{-1}]^{0,5} = n.Q^{0,5}.E^{-0,75}$$

Specific rotation

$$n_q = 333\, n_b = 333\, n \frac{Q^{1/2}}{E^{3/4}}$$

$$n_s = 1200\, n \frac{Q^{1/2}}{E^{3/4}} \eta^{1/2}$$



$$E\,\eta_h = u_1\,c_{u1}, \qquad E'\,\eta'_h = u'_1\,c'_{u1}$$

$$E\,\eta_h = k\,u_1^2, \qquad E'\,\eta'_h = k\,u_1'^2$$

$$\frac{u_1}{u'_1} = \frac{n}{n'} = \left(\frac{E}{E'}\right)^{1/2}$$

$$\frac{Q}{Q'} = \frac{c_{m1}}{c'_{m1}} = \frac{u_1}{u'_1} = \left(\frac{E}{E'}\right)^{1/2}$$

$$\frac{P}{P'} = \frac{Q\,E}{Q'\,E'} = \left(\frac{E}{E'}\right)^{3/2}$$

$$\frac{M}{M'} = \frac{P}{P'}\,\frac{n'}{n} = \frac{E}{E'}$$

Distributor – sizing and parameters

$$\pi D_1 n = \pi D_1' n' , \qquad \frac{n}{n'} = \frac{D_1'}{D_1}$$

$$\frac{Q}{Q'} = \frac{D_1^2}{D'^2_1}$$

Specific parameters

$$n_{1E1D} = \frac{n\,D_1}{\sqrt{E}} \qquad (n_{1H1D} = \frac{n\,D_1}{\sqrt{H}})$$

$$Q_{1E1D} = \frac{Q}{D_1^2\,\sqrt{E}} \qquad (Q_{1H1D} = \frac{Q}{D_1^2\,\sqrt{H}})$$

$$\eta_D = 1 - (1 - \eta_M)\,\sqrt[4]{\frac{D_M}{D_D}}\;\sqrt[10]{\frac{E_M}{E_D}}$$

Suction tube

$$p_{2\,min} = p_3 - \Delta p = p_a - \rho.0{,}5(c_3^2 - c_4^2).\eta_S - \rho.g.H_S - \Delta p$$

$$p_{2\,min}.(\rho.g)^{-1} = H_a - H_S - [0{,}5.(c_3^2 - c_4^2).g^{-1}].\eta_S - \Delta p.(\rho.g)^{-1} > H_w$$

$$H_S \leq H_a - H_w - [0{,}5.(c_3^2 - c_4^2).g^{-1}].\eta_S - \Delta p.(\rho.g)^{-1}$$

$$H_S \leq H_A - \sigma.H$$

$$H_A = 10 - h.900^{-1}$$

n_q (min^{-1})	14	28	56	82	112	140	164	192	224
σ_d (1)	0,02	0,05	0,11	0,20	0,35	0,57	0,81	1,45	2,15