Turbines Hydrauliques

...au fil de l’eau

Exemple

$Q = 71.5\ m^3/s$

$H = 543\ m$

$\beta_2 = 22^o$

$u_2 = 40{,}9\ m/s$

$\eta_h = 96\%$

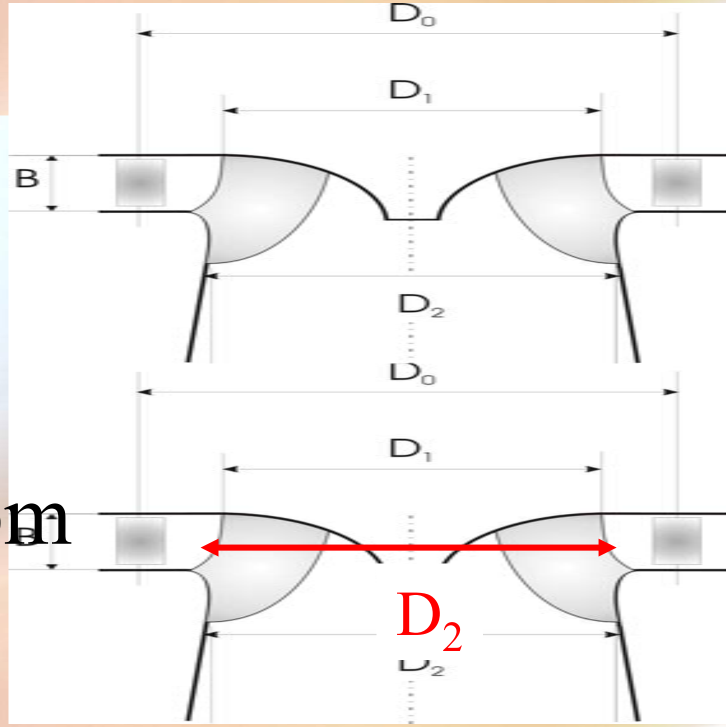
$c_{m2} = c_{m1}$

Trouver D_2 et n

$$D_2 = \sqrt{\frac{4 \cdot Q}{\pi \cdot c_{m2}}} = \sqrt{\frac{4 \cdot Q}{\pi \cdot u_2 \cdot \tan \beta_2}}$$

$$D_2 = \sqrt{\frac{4 \cdot 71{,}5}{\pi \cdot 40 \cdot \tan 22^\circ}} = 2.37\text{m}$$

$$n = \frac{u_2 \cdot 60}{\pi \cdot D_2} = \frac{40 \cdot 60}{\pi \cdot 2.37} = 322 \text{ rpm}$$



Dimensions à l'entrée

$$\eta_h = \frac{u_1 \cdot c_{u1} - u_2 \cdot c_{u2}}{g \cdot H}$$

Au point nominal, $c_{u2} = 0$

$$\eta_h = 0.96 = \frac{u_1 \cdot c_{u1}}{g \cdot H}$$

$$c_{u1} = \frac{g \cdot H \cdot 0{,}96}{u_1}$$

Dimensions à l'entrée

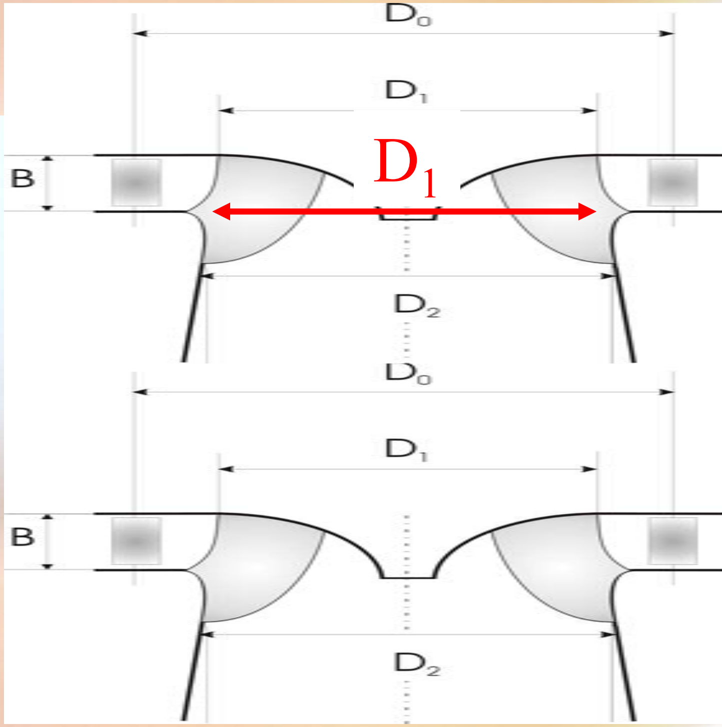
Diamètre D_1

$$u_1 = \sqrt{2 \cdot g \cdot h} = \sqrt{2 \cdot 9{,}81 \cdot 543} = 103{,}22\ {}^{m}\!/_{s}$$

$$u_1 = \omega \cdot \frac{D_1}{2} = \frac{n \cdot 2 \cdot \pi}{60} \cdot \frac{D_1}{2}$$

$$D_1 = \frac{u_1 \cdot 60}{n \cdot \pi} = \frac{103.22 \cdot 60}{322\pi} = 6.12m$$

$$c_{u1} = \frac{g \cdot H \cdot 0{,}96}{u_1} = 49.5$$



Dimensions à l'entrée

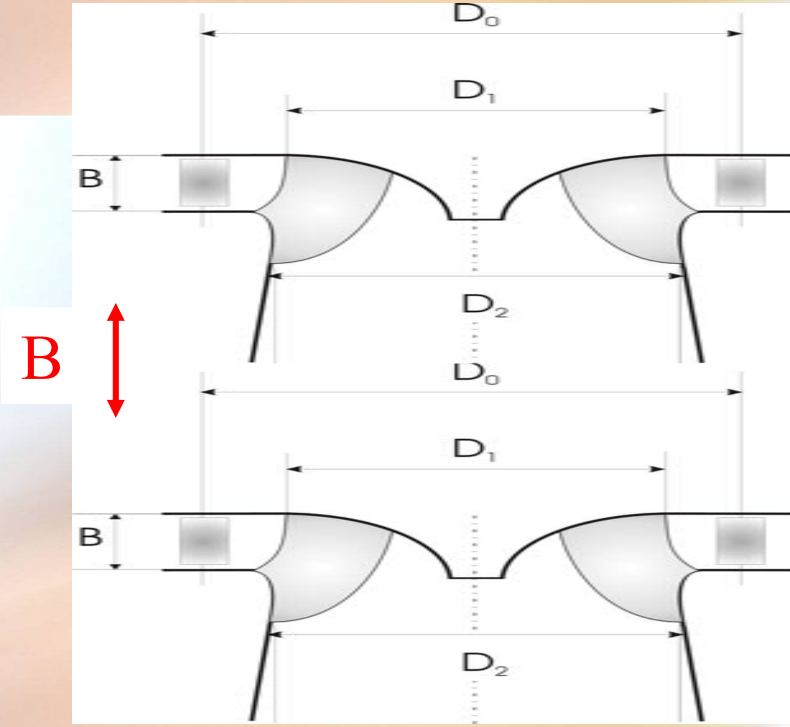
Hauteur B

Continuité: $c_{m1} \cdot A_1 = c_{m2} \cdot A_2$

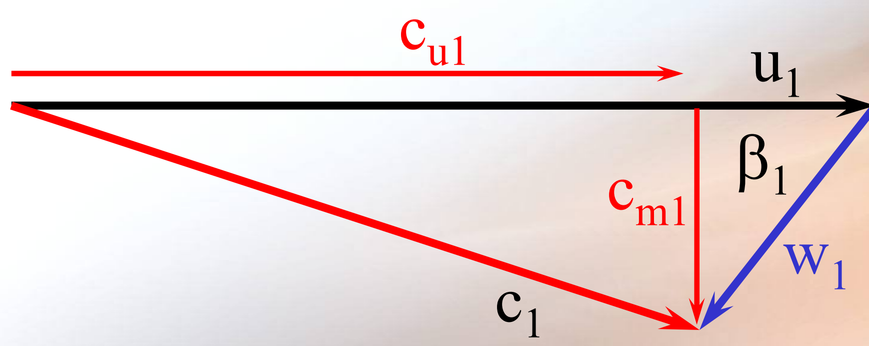
Donnée: $c_{m2} = c_{m1}$

$$B \cdot D_1 \cdot \pi = \frac{\pi \cdot D_2^2}{4}$$

$$B = \frac{D_2^2}{4 \cdot D_1} = \frac{2.37^2}{4 \cdot 6.12} = 0{,}23m$$

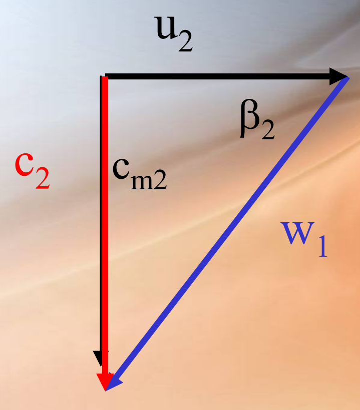


Angle β_1 à l'entrée

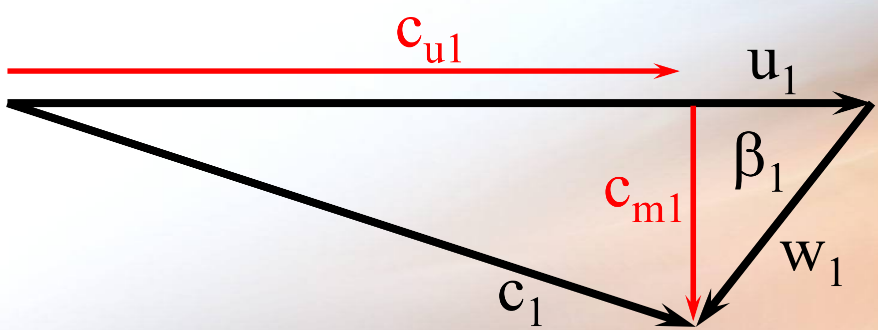


$$c_{m1} = c_{m2} = \tan\beta_2 \cdot u_2 = \tan 22^\circ \cdot 40\,{}^{m}\!/_{s} = 16.2\,{}^{m}\!/_{s}$$

$$(c_{m2} = u_2 \ \tan\beta_2 (\text{sortie axiale}))$$



Angle β_1 à l'entrée



$$\tan \beta_1 = \frac{c_{m1}}{u_1 - c_{u1}}$$

$$\beta_1 = \arctan\left(\frac{c_{m1}}{u_1 - c_{u1}}\right) = \arctan\left(\frac{16.2}{103,2 - 49,5}\right) = 16.78^\circ$$

Vitesse synchrone

La vitesse du générateur est donnée par le nombre de pôles et par la fréquence du réseau

$$n[rpm] = \frac{60\, x\, f}{z_p}$$

$$f = \frac{z_p n}{60}$$

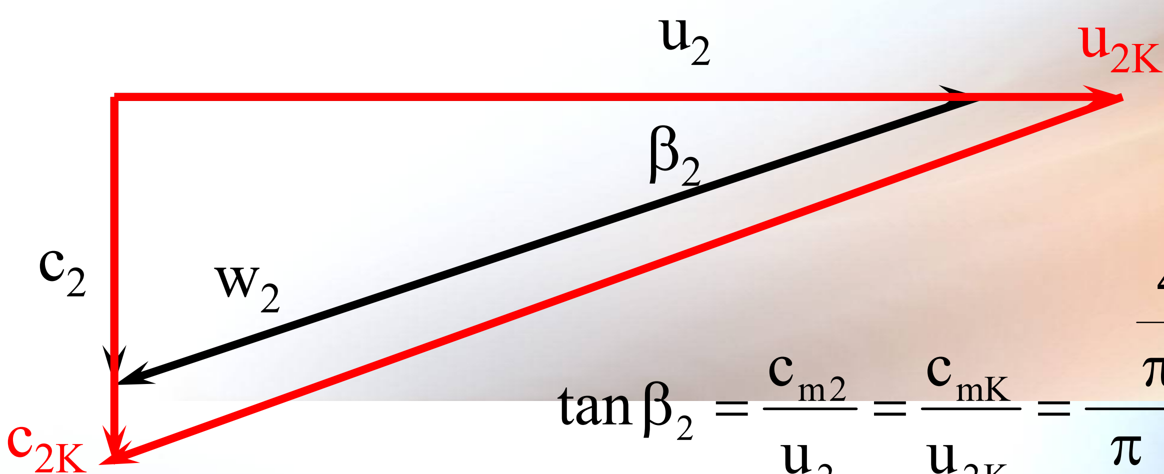
Correction de la vitesse de rotation

$$z_p = \frac{3000}{n} = 9.3 \quad (f = 50)$$

$$avec\, z_p = 9 \quad \Rightarrow \quad n_K = \frac{3000}{9} = 333\ rpm$$

$$\mathrm{n} = \frac{\mathrm{u_2} \cdot 60}{\pi \cdot \mathrm{D_2}} = \frac{40 \cdot 60}{\pi \cdot 2.37} = 322\ \mathrm{rpm}$$

On garde le triangle de vitesses



$$\tan\beta_2 = \frac{c_{m2}}{u_2} = \frac{c_{mK}}{u_{2K}} = \frac{\frac{4\cdot Q}{\pi\cdot D_2^2}}{\frac{\pi}{60}\cdot n\cdot D_2} = \frac{\frac{4\cdot Q}{\pi\cdot D_{2K}^2}}{\frac{\pi}{60}\cdot n_K\cdot D_{2K}}$$

$$\Downarrow$$

$$n_K\cdot D_{2K}^3 = n\cdot D_2^3$$

$$\Downarrow$$

$$D_{2K} = \sqrt[3]{\frac{h\cdot D_2^3}{h_K}} = 2.373\text{m}\sqrt{\frac{322}{333}} = \underline{\underline{2.35\text{m}}}$$

Exemple II

$Q = 12\ m^3/s$

$\alpha_1 = 15^o$

$D_1 = 1.5\ m$

$D_2 = 1\ m$

$B_2 = 0.2\ m$

$c_1 = 40\ m/s$

$c_{1m} = c_{2m}$

$c_{2u} = 0$

$n = 250\ rpm$

$\eta_h = 97\%$

Trouver u_1, w_1, u_2, w_2, W_e, P, H

$$u_1 = \frac{\pi \cdot D_1 \cdot n}{60} = 19.63\ m/s$$

$$w_{1m} = c_1\, \boldsymbol{sin}\, \alpha = 10.35\ m/s$$

$$w_{1u} = c_1\, \boldsymbol{cos}\, \alpha - u_1 = 19\ m/s$$

$$w_1 = \sqrt{w_{1u}^2 + w_{1m}^2} = 21.64\ m/s$$

$$u_2 = \frac{\pi \cdot D_2 \cdot n}{60} = 13.09\ m/s$$

$$w_2 = \frac{Q}{\pi D_2 B_2 \rho} = 19.1\ m/s$$

$$c_2 = \sqrt{w_2^2 - u_2^2} = 13.91\ m/s$$

$$W_e = c_1 \boldsymbol{cos}\,\alpha_1 u_1 = 758.64\ J/kg$$

$$\dot{W} = \eta_h \rho Q W_e = 8830.53\ kW$$

Exemple III

$Q = 3\ m^3/s$

$\xi_1 = 0.65$

$\xi_2 = 0.43$

$b_1/\ D_1 = 0.115$

f=50 cycles/sec

$\eta_h = 0.85$

$n_s < 115$ (P en CV)

H=200 m

Trouver P, rpm, D_1 D_2

$$P = \rho g Q H \eta = 9.8 \times 1000 \times 3 \times 200 \times 0.85 = 4998 kW$$

$$n_S = \frac{n\sqrt{P}}{H^{5/4}}$$

P=P/75=6664 CV

$$n_S = \frac{n\sqrt{6664}}{200^{5/4}} = 0.1085n$$

$$0.1085n < 115 \quad \Rightarrow \quad n < \frac{115}{0.1085} = 1059.6 \ rpm$$

$$z_p n = 60 \times f = 60 \times 50 = 3000$$

$$z_p = 3 \Rightarrow n = \frac{3000}{3} = 1000\ rpm$$

$$n_S = 0.1085n = 108.5 \quad \Rightarrow Francis\ \ lente$$

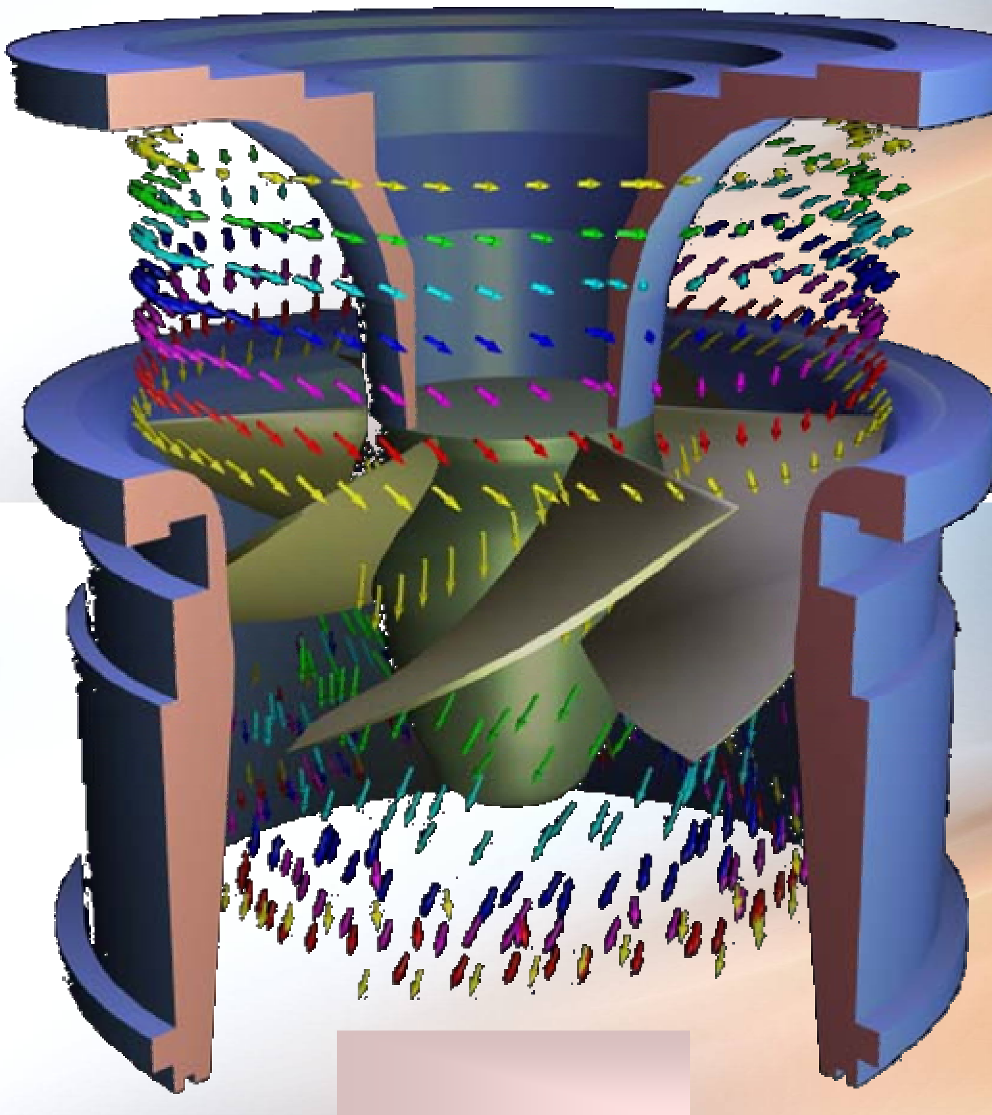
$$u_1 = \xi_1 \sqrt{2gH} = 0.65\sqrt{2g \times 200} = 40.7\ m/s$$

$$u_1 = \frac{\pi \cdot D_1 \cdot n}{60} \Rightarrow D_1 = 0.773\ m$$

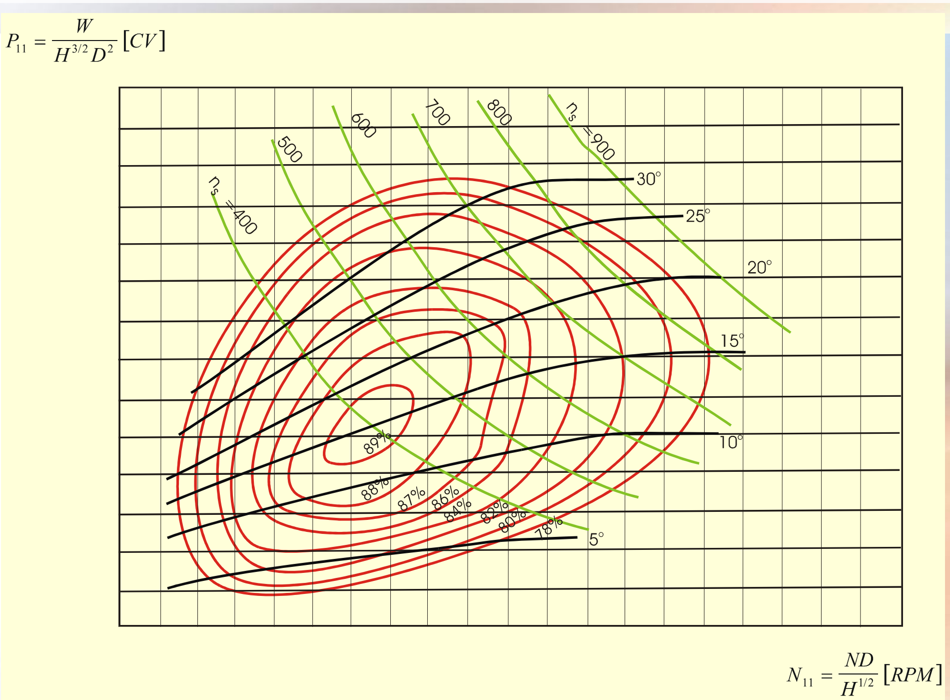
$$u_2 = \xi_2 \sqrt{2gH} = 0.43\sqrt{2g \times 200} = 26.9\ m/s$$

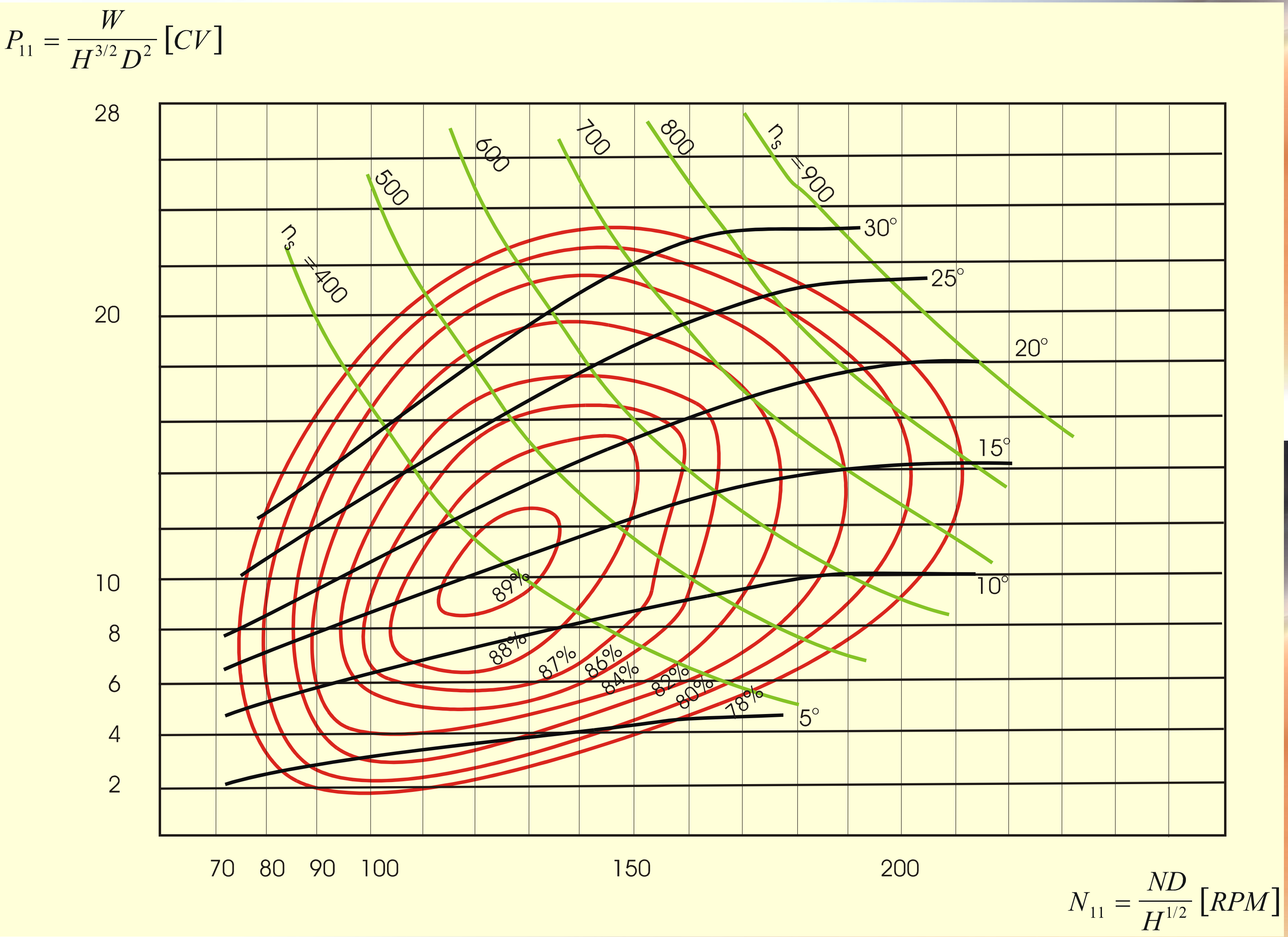
$$u_2 = \frac{\pi \cdot D_2 \cdot n}{60} \Rightarrow D_2 = 0.5138\ m$$

$$\frac{b_1}{D_1} = 0.115 \Rightarrow b_1 = 0.773\ m \times 0.115 = 0.0889m$$



- Trouver la vitesse de rotation le diamètre du rotor et la puissance produite par une turbine Kaplan dans une installation avec une chute de H=40m. La puissance cherchée et de 17800 CV. La turbine opère à une vitesse spécifique de n_s =400 dont la colline de rendement est :





$P_{11} = \frac{W}{H^{3/2} D^2} [CV]$
28
20
10
8
6
4
2
70
80
90
100
150
200
$N_{11} = \frac{ND}{H^{1/2}} [RPM]$
$n_s = 400$
500
600
700
800
$n_s = 900$
30°
25°
20°
15°
10°
5°
89%
88%
87%
86%
84%
82%
80%
78%

$$n_s = \frac{NP^{1/2}}{H^{5/4}} \quad \Rightarrow \quad N = \frac{n_s H^{5/4}}{P^{1/2}}$$

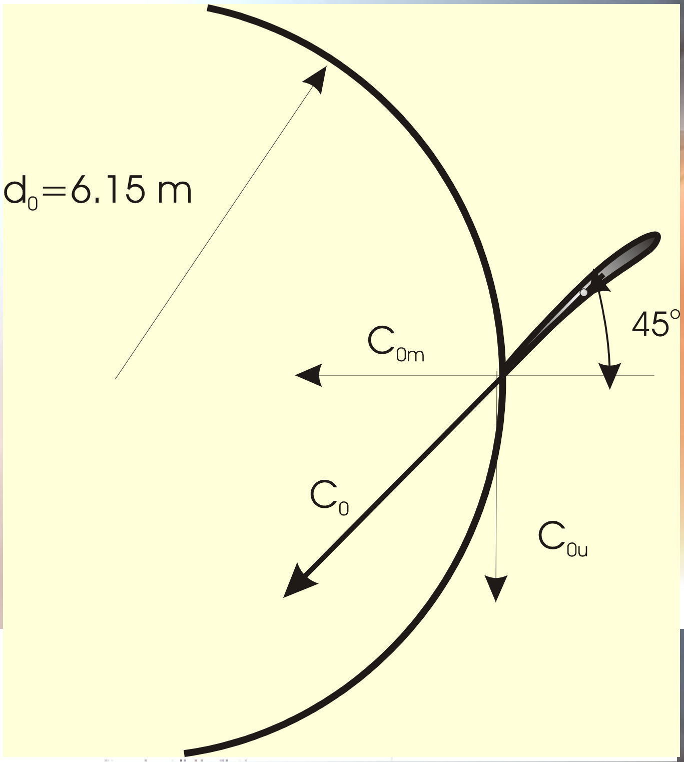
$$N = \frac{400 \times 40^{5/4}}{17800^{1/2}} = 300\ rpm$$

$$N_{11} = \frac{ND}{H^{1/2}}\ rpm \quad \Rightarrow \quad D = \frac{N_{11} H^{1/2}}{N}$$

$$D = \frac{123 \times 40^{1/2}}{300} = 2.6\ m$$

- La chute d'une turbine Kaplan de 67700 KW (92109 CV) est de H=34 mètres et le débit est Q= 225 m^3/s. L'hauteur du distributeur est B=1.88 m et le diamètre à la sortie de celui-ci est d_0 =6.15 m. Le diamètre du moyeu du rotor est d=2.9 m.
- Considérez que la vitesse absolue à la sortie du distributeur est à 45 degrés par rapport à la direction périphérique Également, supposez que la composante C_m reste constante au travers du rotor($C_{m1} = C_{m2}$)
- Calculez
  - les vitesses C_{1u} à la racine(R=1,45 m), au milieu(R=2.15 m et au sommet (R=2.85 m) de l'aube
  - La vitesse de rotation si n_s=460
  - l'angle $\beta_1$pour les trois niveaux indiqués

$$C_{0m} = C_0 \cos 45 = C_0 \sin 45 = C_{0u}$$



$$C_{0m} = \frac{Q}{\pi d_0 B}$$

$$C_{0m} = \frac{225}{\pi \times 6.15 \times 1.88} = 6.2\ m/s$$

$$C_{0u} d_0 = C_{1u} d$$

$$C_{0u} d_0 = 6.2x6.15 = 38.1 = cte$$

$$C_{1u} d_{1my} = 38.1$$

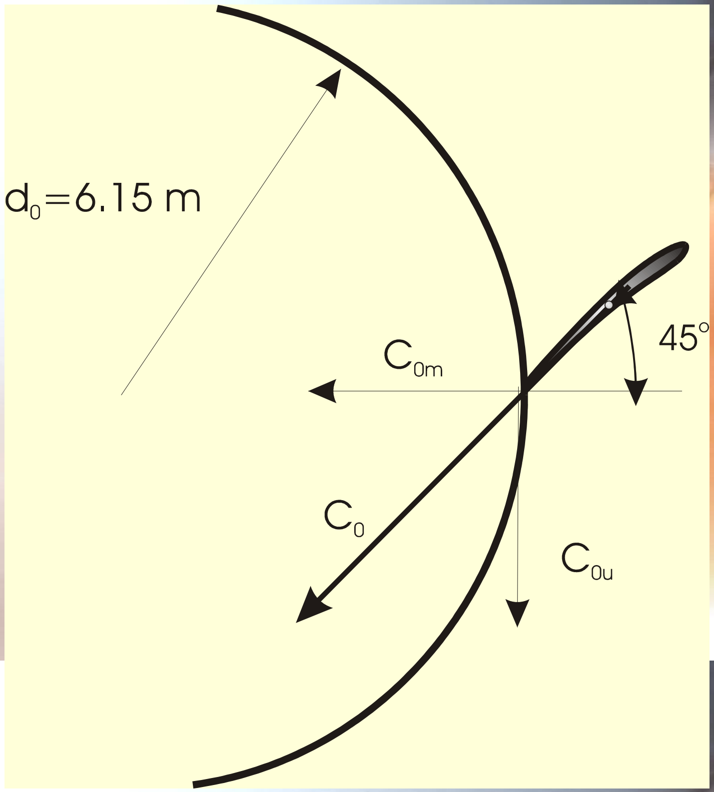
$$C_{1umy} = \frac{38.1}{2.9} = 13.13\ m/s$$

$$C_{1uc} d_{1c} = 38.1$$

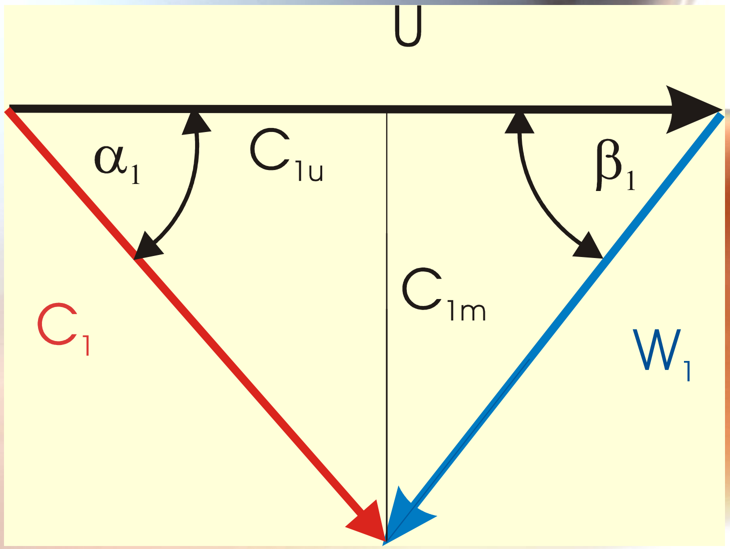
$$C_{1uc} = \frac{38.1}{4.3} = 8.85\ m/s$$

$$C_{1us} d_{1s} = 38.1$$

$$C_{1us} = \frac{38.1}{57} = 6.68\ m/s$$



$$\tan\beta_1 = \frac{C_{1m}}{U - C_{1u}}$$

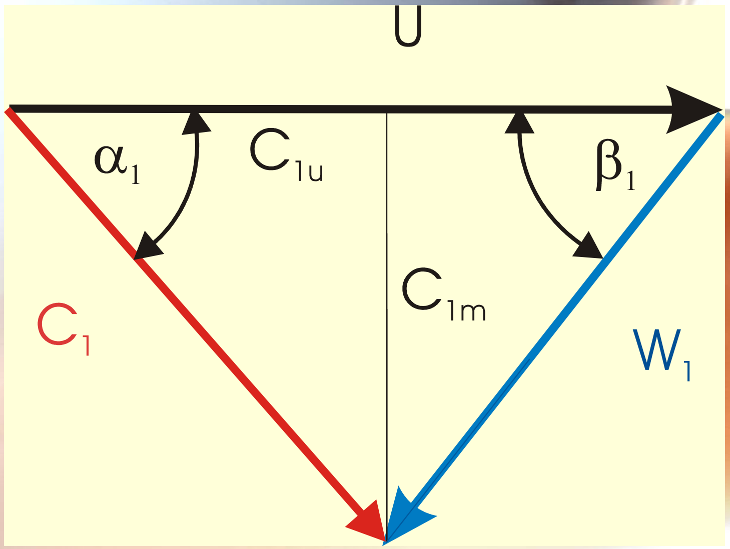


$$N = \frac{n_s H^{5/4}}{P^{1/2}}$$

$$N = \frac{460 \times 34^{5/4}}{92109^{1/2}} = 124.4\ rpm$$

$$U = \pi D N \quad \Rightarrow \quad U_{1M} = 19\ m/s \quad U_{1C} = 28.1\ m/s \quad U_{1S} = 38.3\ m/s$$

$$\tan \beta_1 = \frac{C_{1m}}{U - C_{1u}}$$

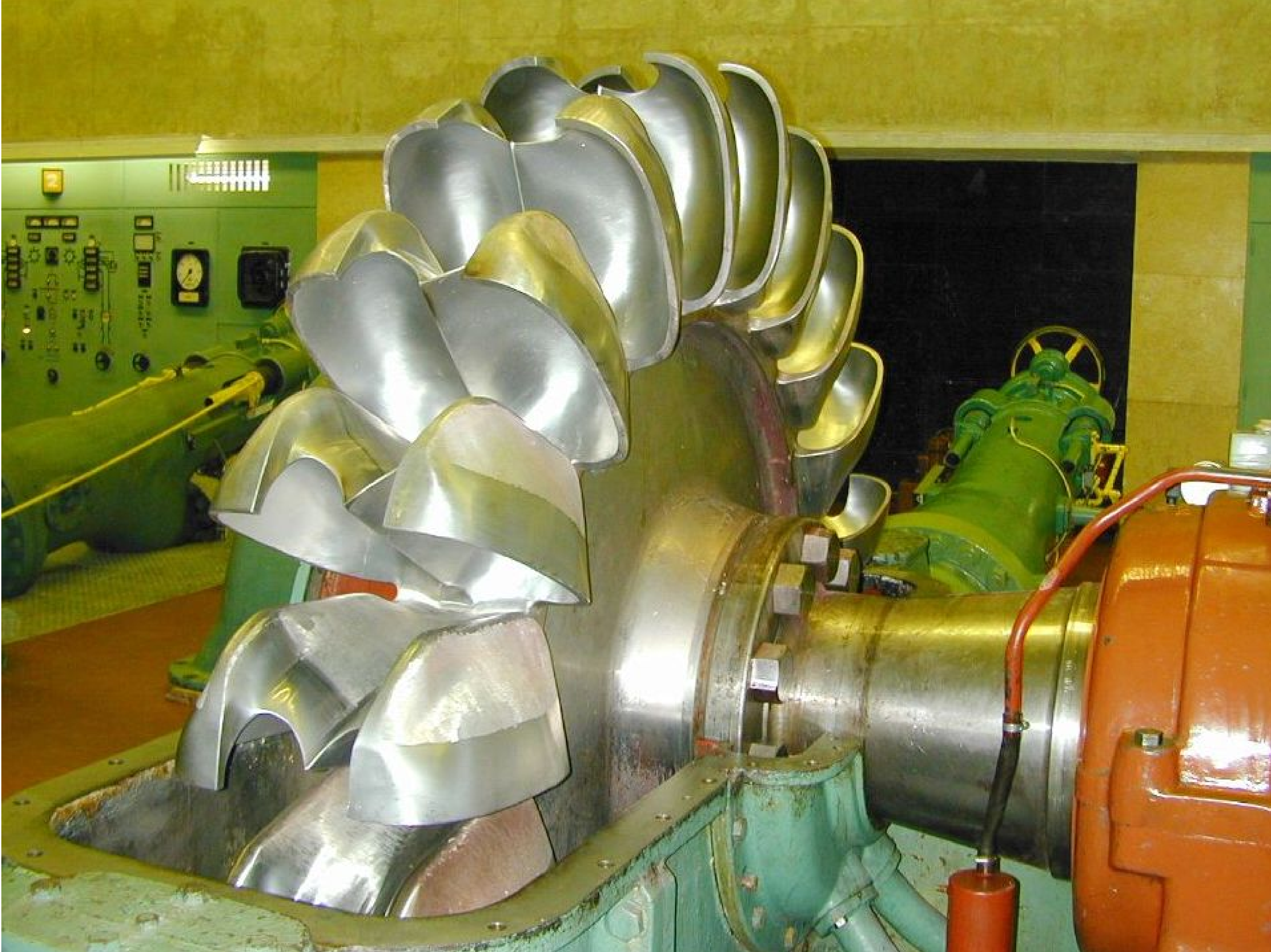


$$\tan \beta_{m1} = \frac{C_{1m}}{U - C_{1um}} = \frac{11.6}{19.0 - 13{,}13} = 1.976$$

$$\beta_{m1} = 63^o$$

$$\beta_{c1} = 31^o$$

$$\beta_{c1} = 20^o$$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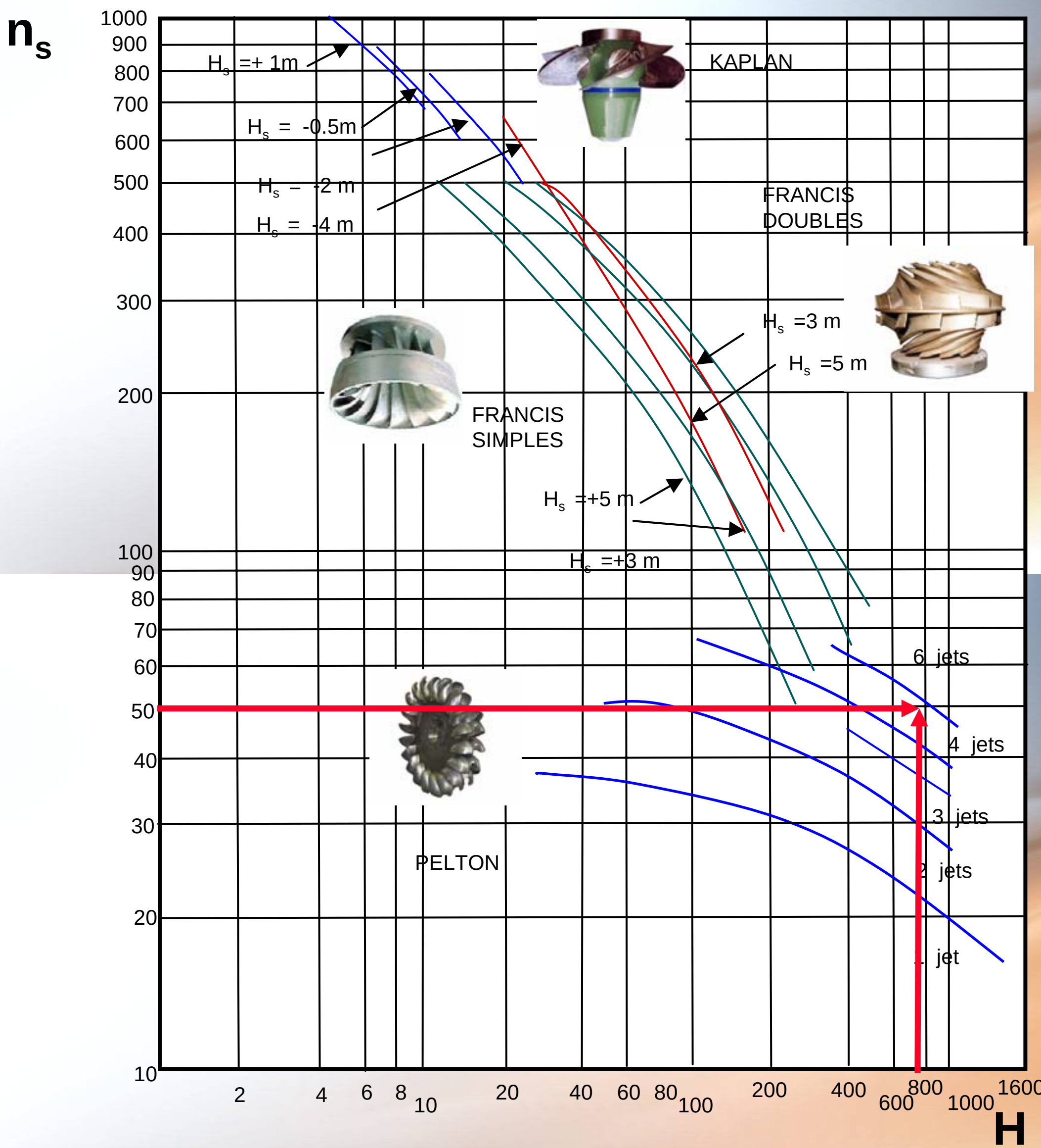
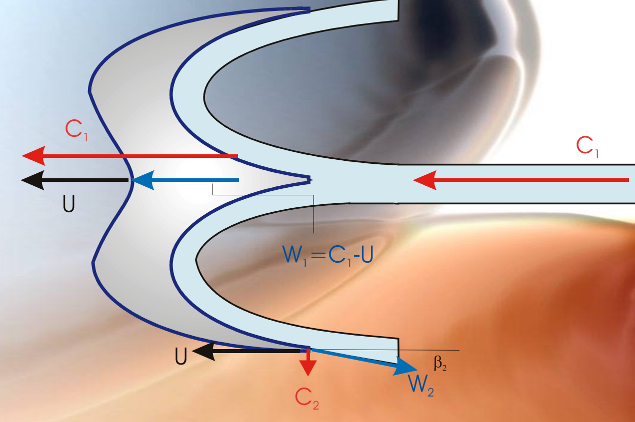
1) Une installation hydroélectrique a les caractéristiques suivantes: P = 45 MW, H = 720 m, n = 720 rpm, η= 0.9,
2) Déterminer
   - Le type de turbine
   - Le débit
   - Les composantes des vitesses (d=1.5m)

$$n_s = \frac{NP^{1/2}}{H^{5/4}} = n_s = \frac{720X(45X10^6 / 735)^{1/2}}{720^{5/4}} = 49.7$$

$$c_1 = \sqrt{2gH} = 118.85 m/s$$



n_s
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
H_s =+ 1m
H_s = -0.5m
H_s = -2 m
H_s = -4 m
KAPLAN
FRANCIS
DOUBLES
H_s =3 m
H_s =5 m
FRANCIS
SIMPLES
H_s =+5 m
H_s =+3 m
6 jets
4 jets
3 jets
2 jets
1 jet
PELTON
2
4
6
8
10
20
40
60
80
100
200
400
600
800
1000
1600
H



$$W^2 + U^2 - 2UW\cos\beta_2 = C_2^2$$

$$Q = \frac{P}{\rho g \eta H} = 6.8 m^3 / s$$

$$u = \frac{2\pi n}{60}\frac{D}{2} = 58.9 m / s$$

$$w_1 = c_1 - u = 59.95 m / s$$

$$w_2 = w_1 = 59.95 m / s$$

1) Une turbine Pelton a les caractéristiques suivantes:
   $H = 402$ m, $D_s = 108$ mm, $\alpha_1=0^o$, $\beta_2=15^o$ $\eta= 0.9$, $z_i = 4$
2) Déterminer
   - Le débit, la puissance théorique maximale
   - La valeur absolue de la vitesse c_2 s'il y a une perte du 10% de la valeur de la vitesse relative lors du passage par l'aube
   - La puissance théorique disponible
   - Le rendement hydraulique idéal

$$c_1 = \sqrt{2gH} = 88.81 m/s$$

$$A_{jet} = \frac{\pi D^2}{4}$$

$$H_{idéal} = \frac{R\omega(V_{jet} - R\omega)(1+\cos\beta_2)}{g}$$

$$A_{jet} = \frac{\pi(0.108)^2}{4} = 0.0092\,m^2$$

$$Q = 4\times c_1 \times A_{jet} = 4\times 88.81\frac{m}{s}\times 0.0092m^2 = 3.268\frac{m^3}{s}$$

$$P_{idéale} = \rho Q R\omega(V_{jet} - R\omega)(1+\cos\beta_2)$$

$$u = R\omega = \frac{V_{jet}}{2}$$

$$P_{idéale} = 1000 \times 3.268 \times \frac{88.81}{2} \times \frac{88.81}{2}\left(1 + \cos 15^o\right)$$

$$P_{idéale} = 12668\,kW$$

$$W_1 = C_1 - U = C_1 - \frac{C_1}{2} = 44.4\frac{m}{s}$$

$$W_2 = 0.9 \times W_1 = 39.96\frac{m}{s}$$

$$C_2 = \sqrt{W_2^2 + U^2 - 2UW_2 \cos\beta_2} = 11.86\frac{m}{s}$$

$$P_T = \rho g Q H = 1000 \times 9.8 \times 3.268 \times 402 = 12882\,kW$$

$$\eta_h = \frac{P_i}{P_T} = \frac{12668}{12882} = 0.983$$

- Une installation hydroélectrique produit 100 MW dont l'alternateur a 6 paires de pôles ($z_i = 6$) . La chute est de H = 750, le rendement de la turbine est $\eta = 0.9$ et la perte dans la conduite forcée (considérée verticale) est de 0.02 m par m. La fréquence est de 50 cycles

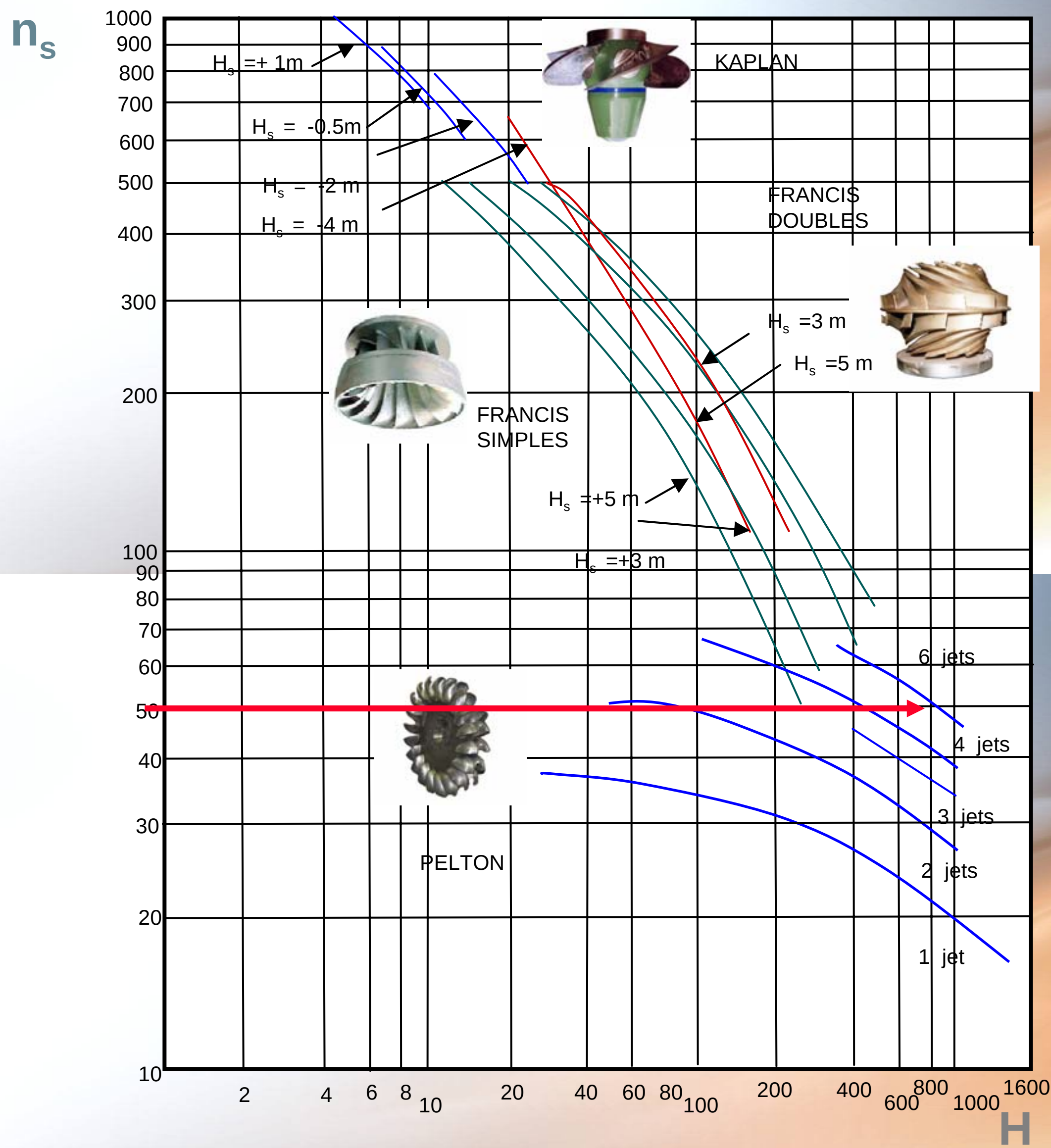
- On doit trouver le type d'alternateur (z_i) pour une turbine similaire (type?, N, n_s) que produira 30 MW pendant la nuit

$$H_n = H - 0.02 \times H = 735\, m$$

$$n_s = \frac{NP^{1/2}}{H^{5/4}} = n_s = \frac{N \times (100 \times 10^6 / 735)^{1/2}}{735^{5/4}} = 0.0964\ N$$

$$N = \frac{60 \times f}{z_i} = \frac{60 \times 50}{6} = 500\, rpm$$

$$n_s = 0.0964\ N = 0.0964 \times 500 = 48.19$$



n_s
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
H$_s$ =+ 1m
H$_s$ = -0.5m
H$_s$ = -2 m
H$_s$ = -4 m
KAPLAN
FRANCIS
DOUBLES
H$_s$ =3 m
H$_s$ =5 m
FRANCIS
SIMPLES
H$_s$ =+5 m
H$_s$ =+3 m
6 jets
4 jets
3 jets
2 jets
1 jet
PELTON
2
4
6
8
10
20
40
60
80
100
200
400
600
800
1000
1600
H

$$N = \frac{n_s H^{5/4}}{(P/735)^{1/2}} = \frac{48.19 \times 735^{5/4}}{\left(30 \times 10^6 / 735\right)^{1/2}} = 912.849$$

$$z_i = \frac{60 \times f}{N} = \frac{60 \times 50}{912.849} = 3.28$$

$$z_i = 4$$

$$N = \frac{60 \times f}{z_i} = \frac{60 \times 50}{4} = 750\ rpm$$

$$n_s = \frac{NP^{1/2}}{H^{5/4}} = n_s = \frac{N \times (30 \times 10^6 / 735)^{1/2}}{735^{5/4}} = 39.6$$