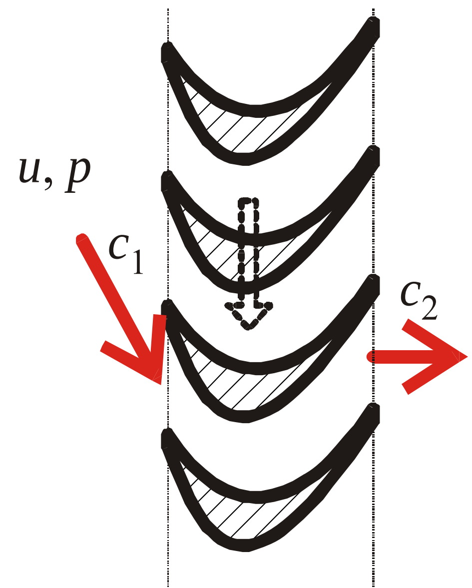
ENERGETSKI STROJI

- Uvod
- Pregled teoretičnih osnov
- Volumetrični stroji
- Turbinski stroji
  - Značilnosti
  - Trikotniki hitrosti
  - Eulerjeva turbinska enačba
  - Notranji izkoristek
  - Energijska karakteristika
- Energetske naprave

PRETOČNI ALI TURBINSKI STROJI

Vrste pretočnih sli volumenskih strojev		
Delovni (gnani) stroji	Aerohidravlični stroji	ČRPALKE PROPELERJI VENTILATORJI
	Toplotni stroji	KOMPRESORJI
Pogonski (gonilni) stroji	Aerohidravlični stroji	VODNE TURBINE VETRNICE
	Toplotni stroji	PLINSKE TURBINE PARNE TURBINE



TURBINSKI STROJI

DELOVNI STROJI

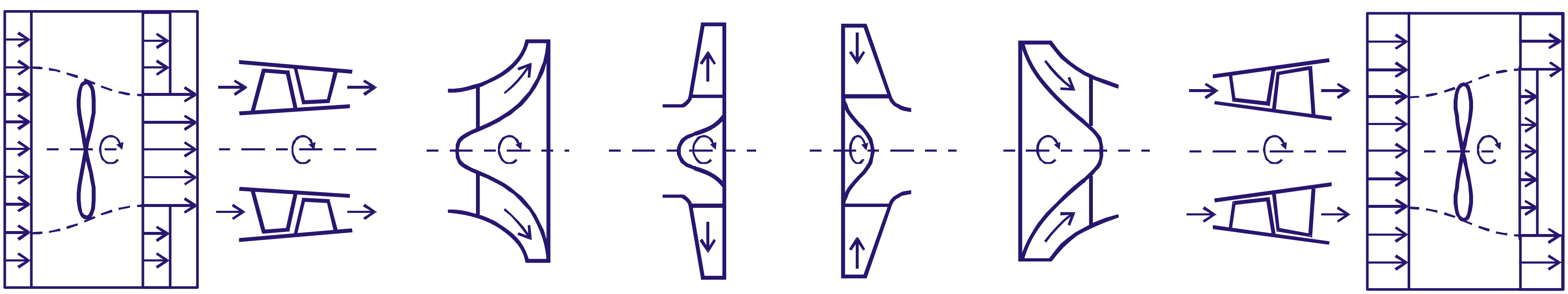
BREZ OKROVA
- PROPELER

Z OKROVOM
- AKSIALNI KOMPRESOR ČRPALKA
- DIAGONALNI KOMPRESOR ČRPALKA
- RADIALNI KOMPRESOR ČRPALKA

POGONSKI STROJI

Z OKROVOM
- RADIALNA TURBINA
- DIAGONALNA TURBINA
- AKSIALNA TURBINA

BREZ OKROVA
- VETRNICA

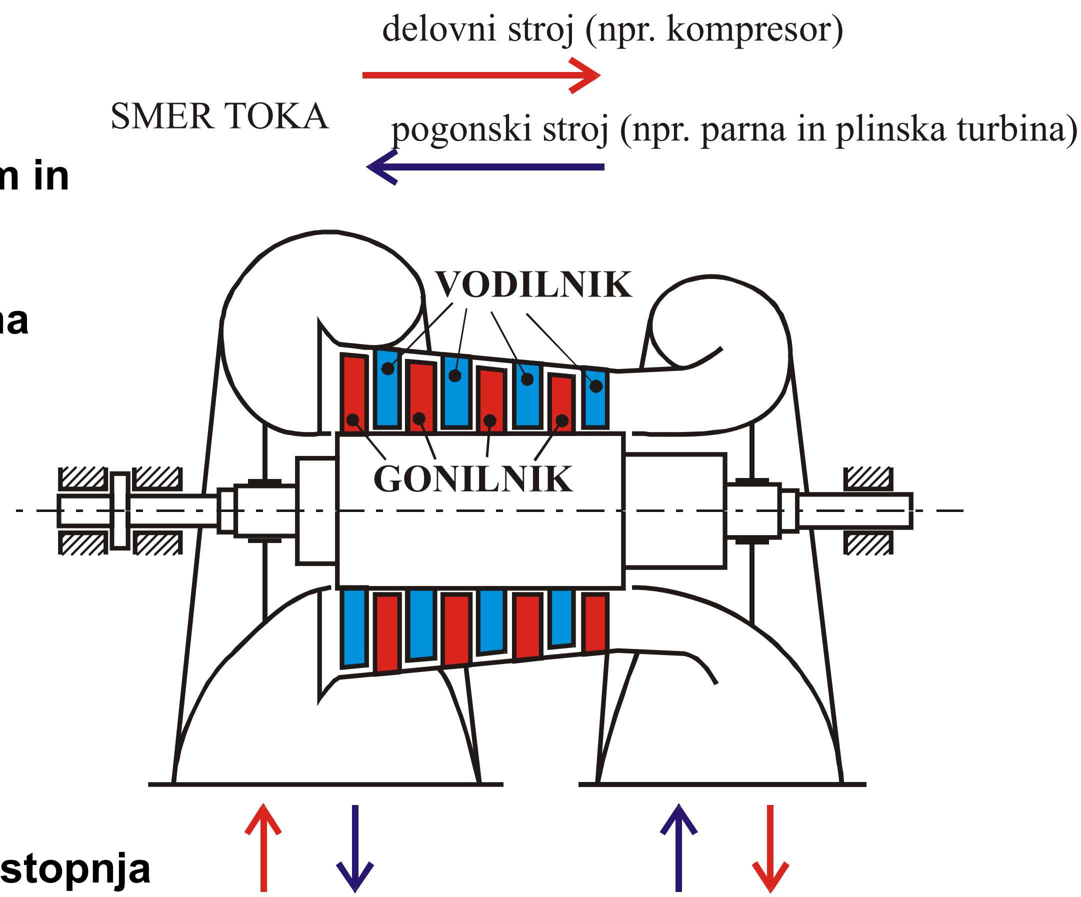


Osnovne značilnosti

kolo z lopaticami

transport energije med fluidom in lopaticami (gonilnikom)

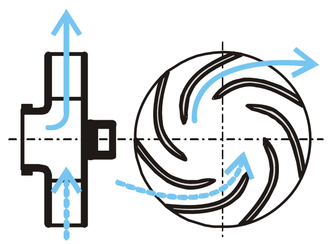
delovna snov plin ali kapljevina



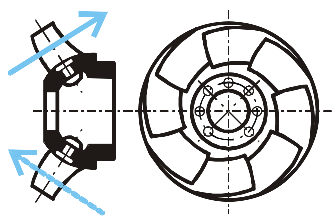
gonilnik + vodilnik (difuzor) = stopnja

možnost nanizanja zaprednih stopenj

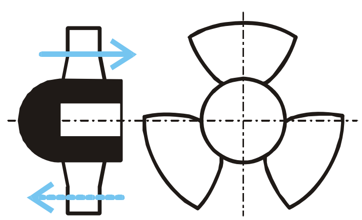
Osnovne smeri toka delovne snovi



radialna

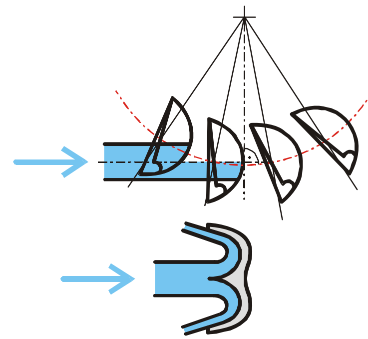


diagonalna

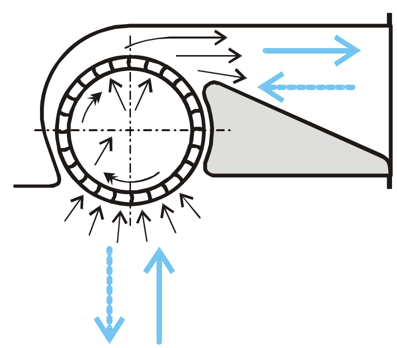


aksialna

tangencialna

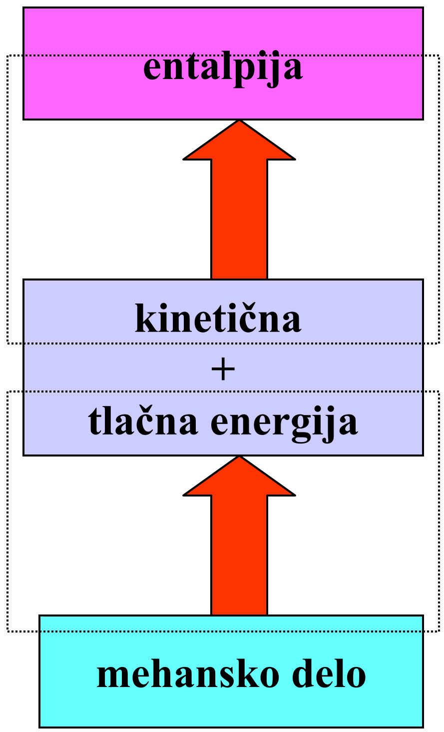


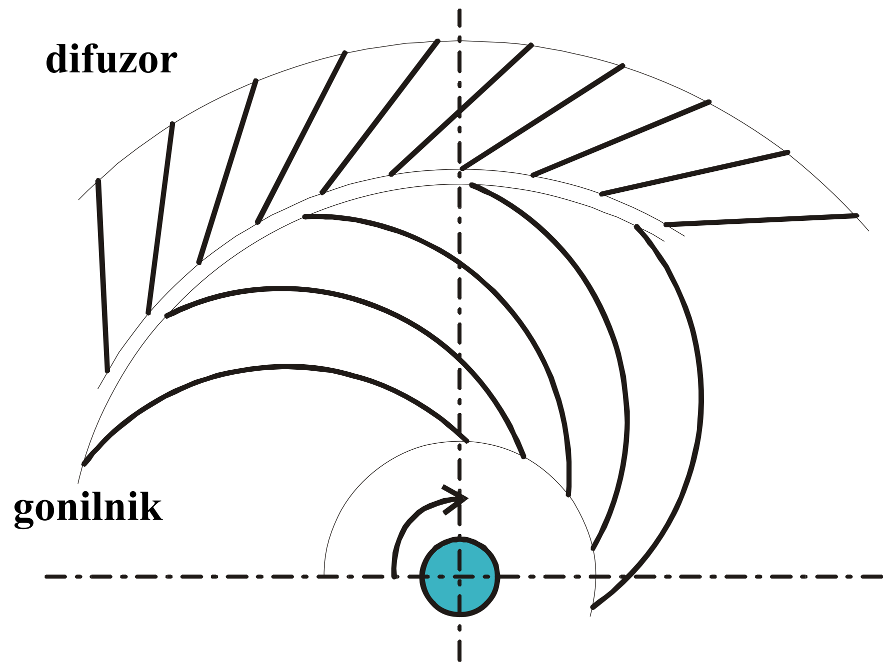
prečna



Način pretvorbe energije pri turbinskih strojih

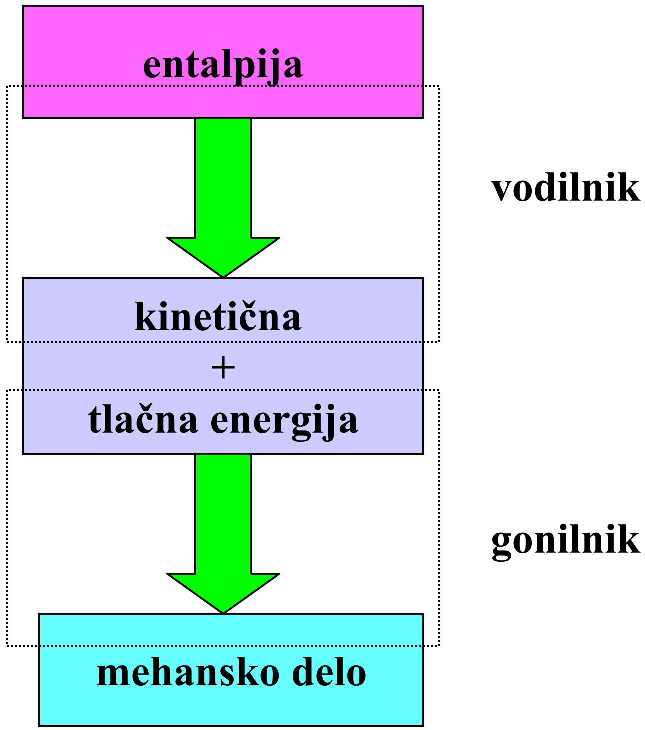
Delovni stroji



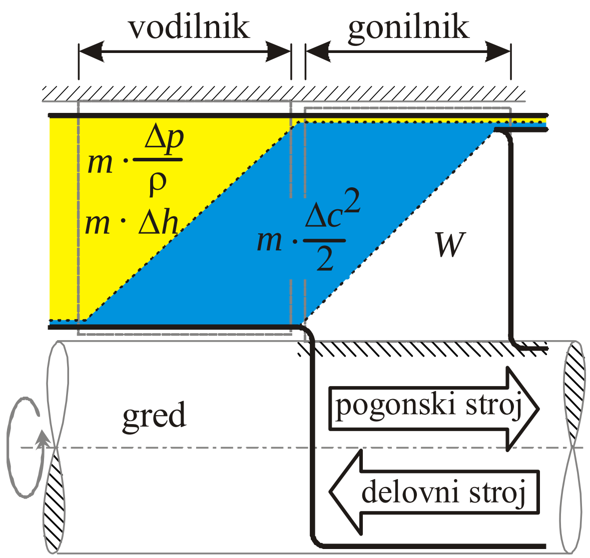


Način pretvorbe energije pri turbinskih strojih

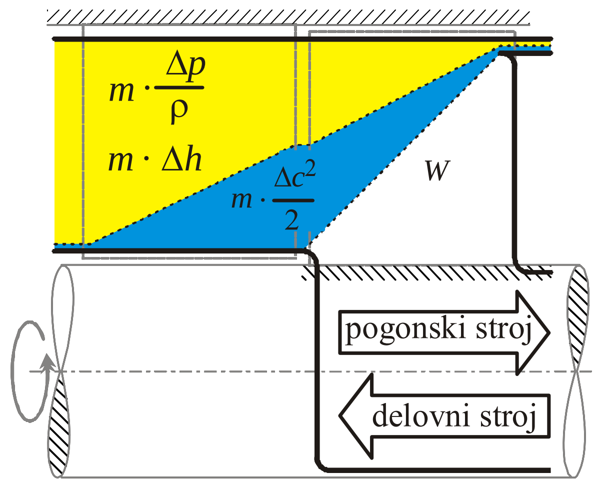
Pogonski stroji



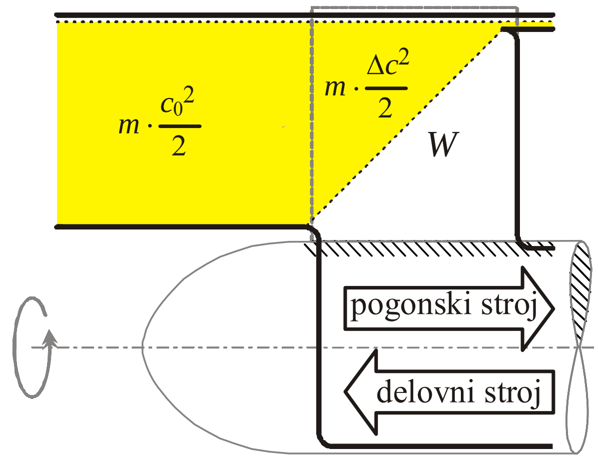
Enakotlačni stroj



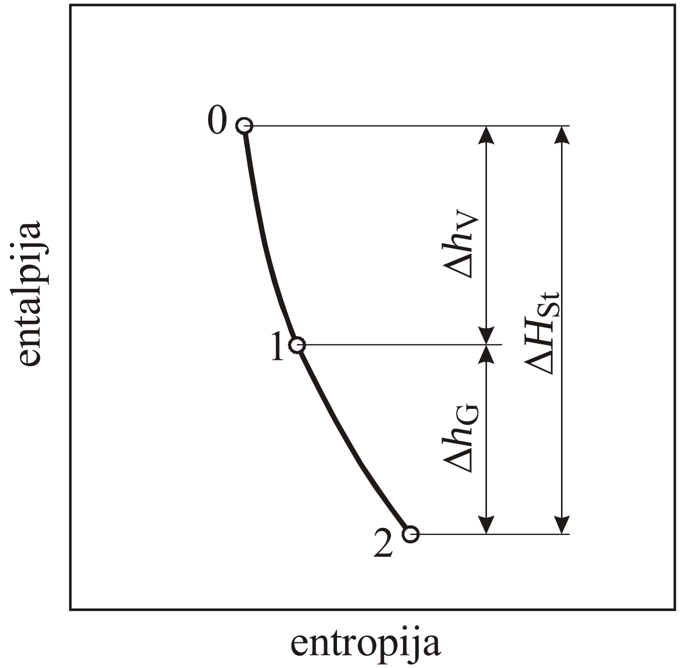
Nadtlačni stroj

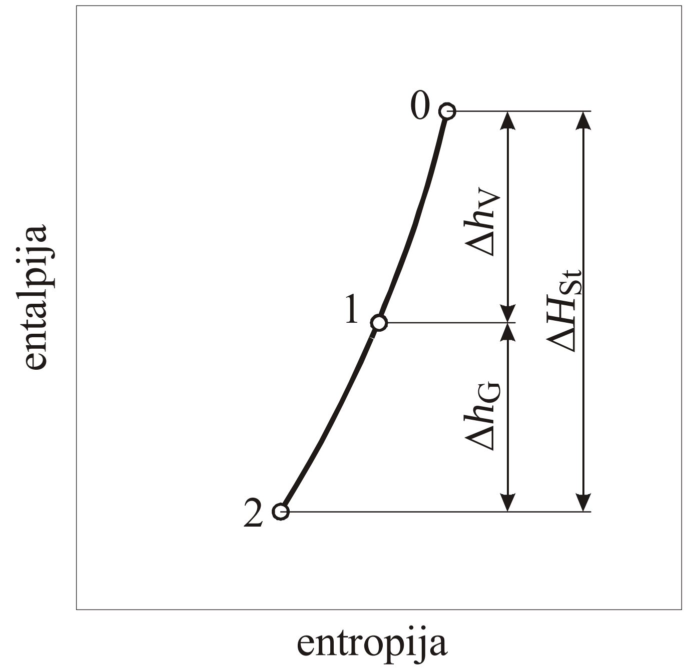


Nadtlačni stroj brez vodilnika



Stopnja reaktivnosti





$$\rho = \frac{\Delta h_G}{\Delta h_V + \Delta h_G} = \frac{\Delta h_G}{\Delta H_{St}}$$

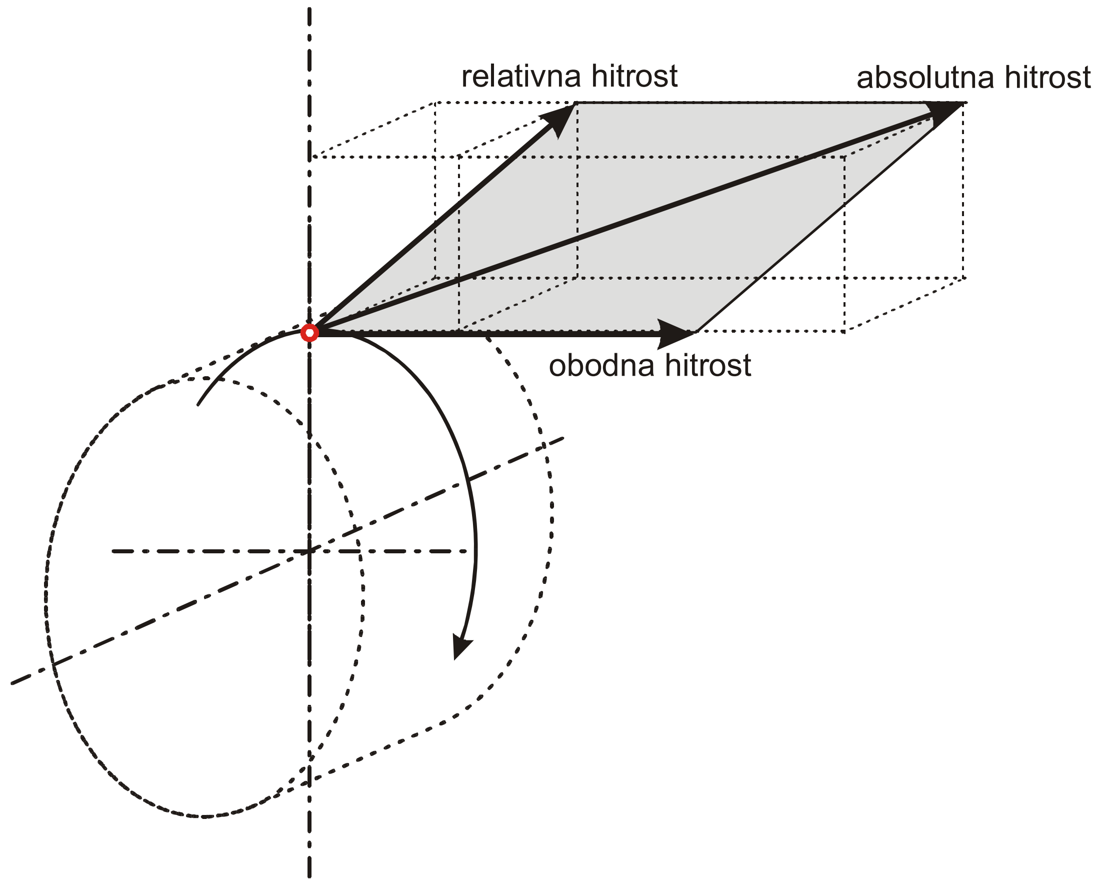
$\rho = 1 \Rightarrow \Delta h_V = 0$ **nadtlačna stopnja**

$\rho = 0{,}5 \Rightarrow \Delta h_V = \Delta h_G$ **nadtlačna stopnja**

$\rho = 0 \Rightarrow \Delta h_V = \Delta H_{St}$ **enakotlačna stopnja**

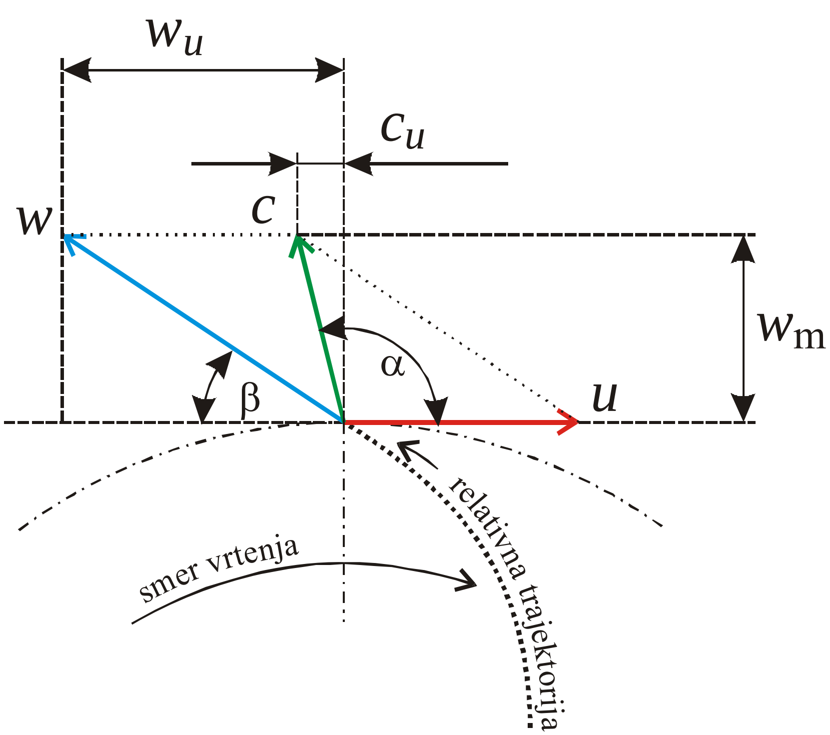
Trikotniki hitrosti

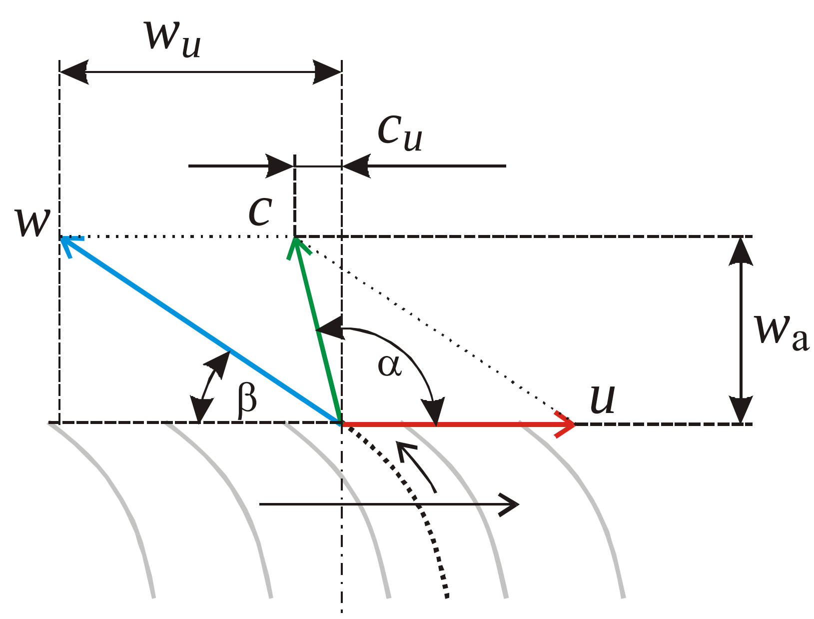
$$\vec{c} = \vec{u} + \vec{w}$$



Trikotniki hitrosti

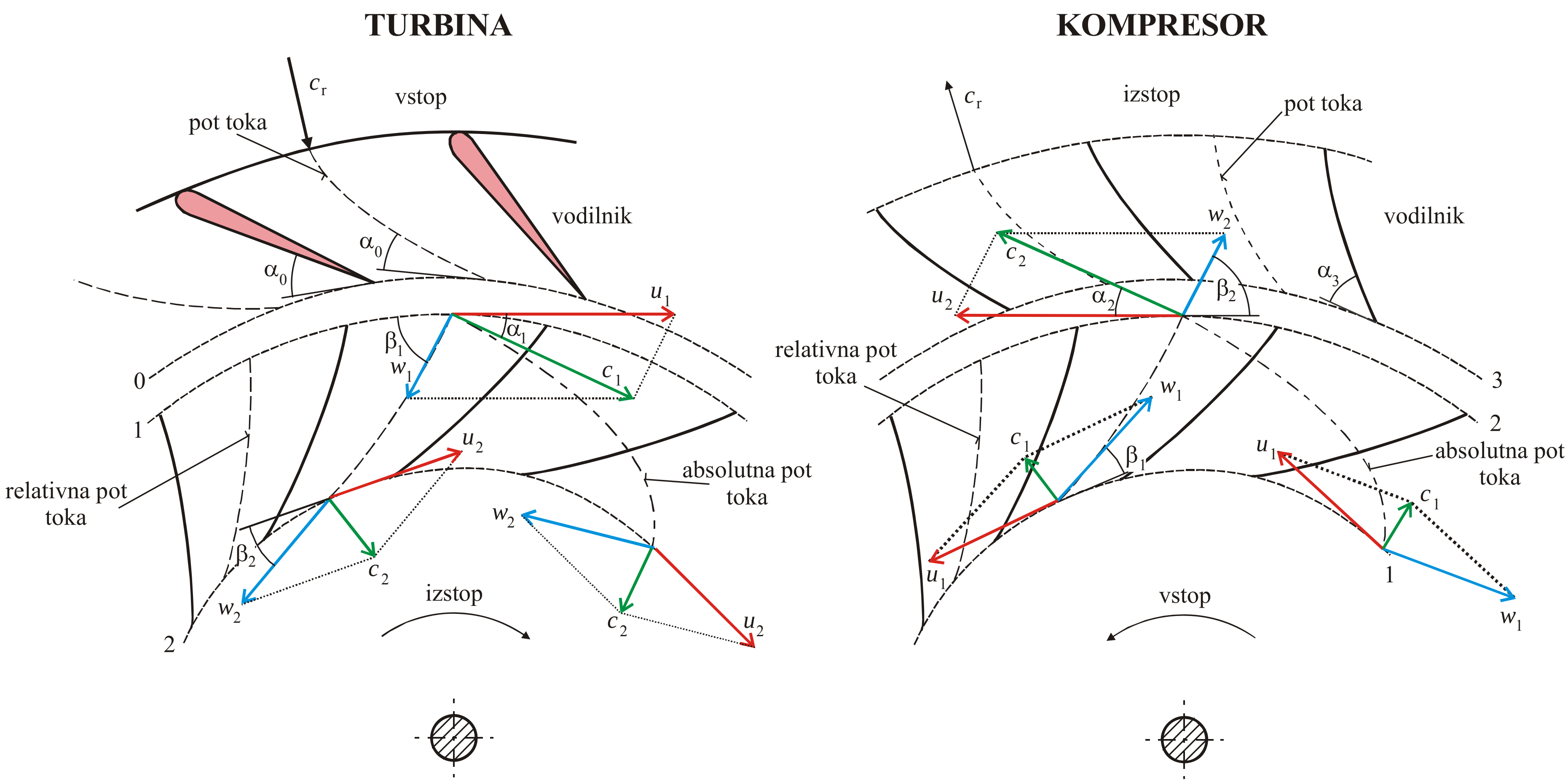
$$\vec{c} = \vec{u} + \vec{w}$$



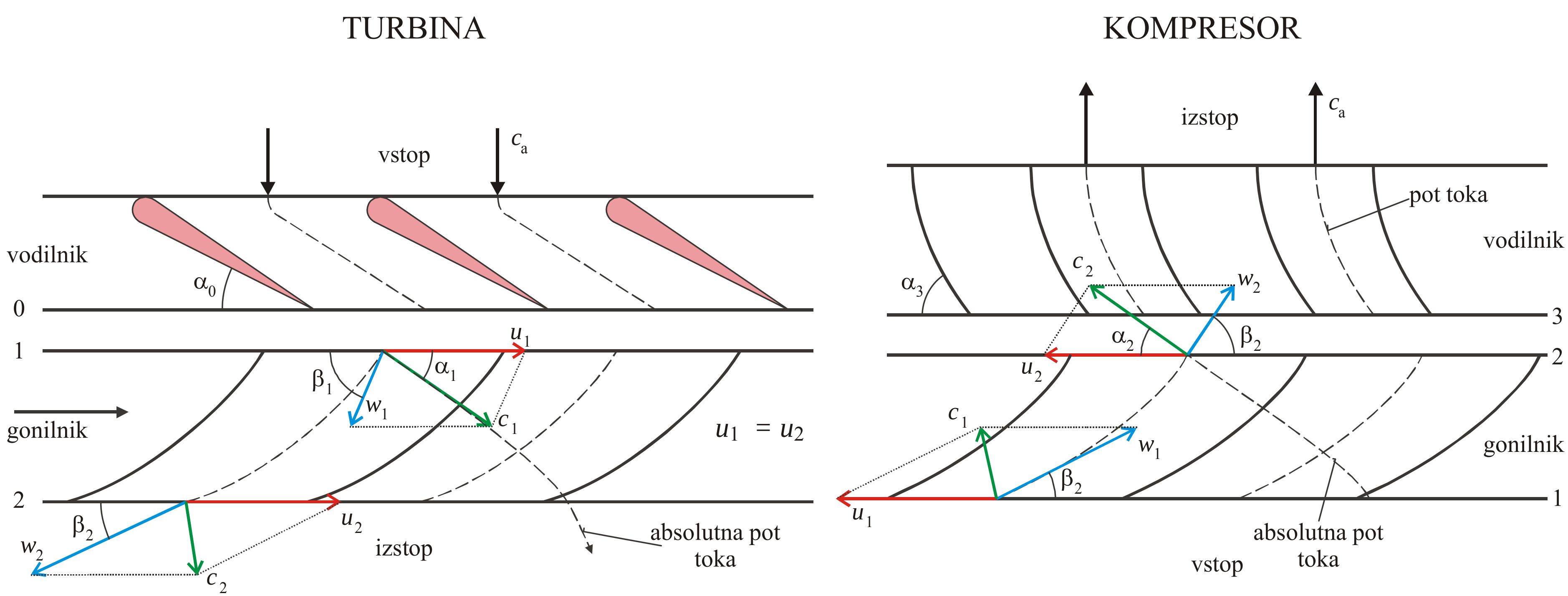


RADIALNI STROJI	AKSIALNI STROJI

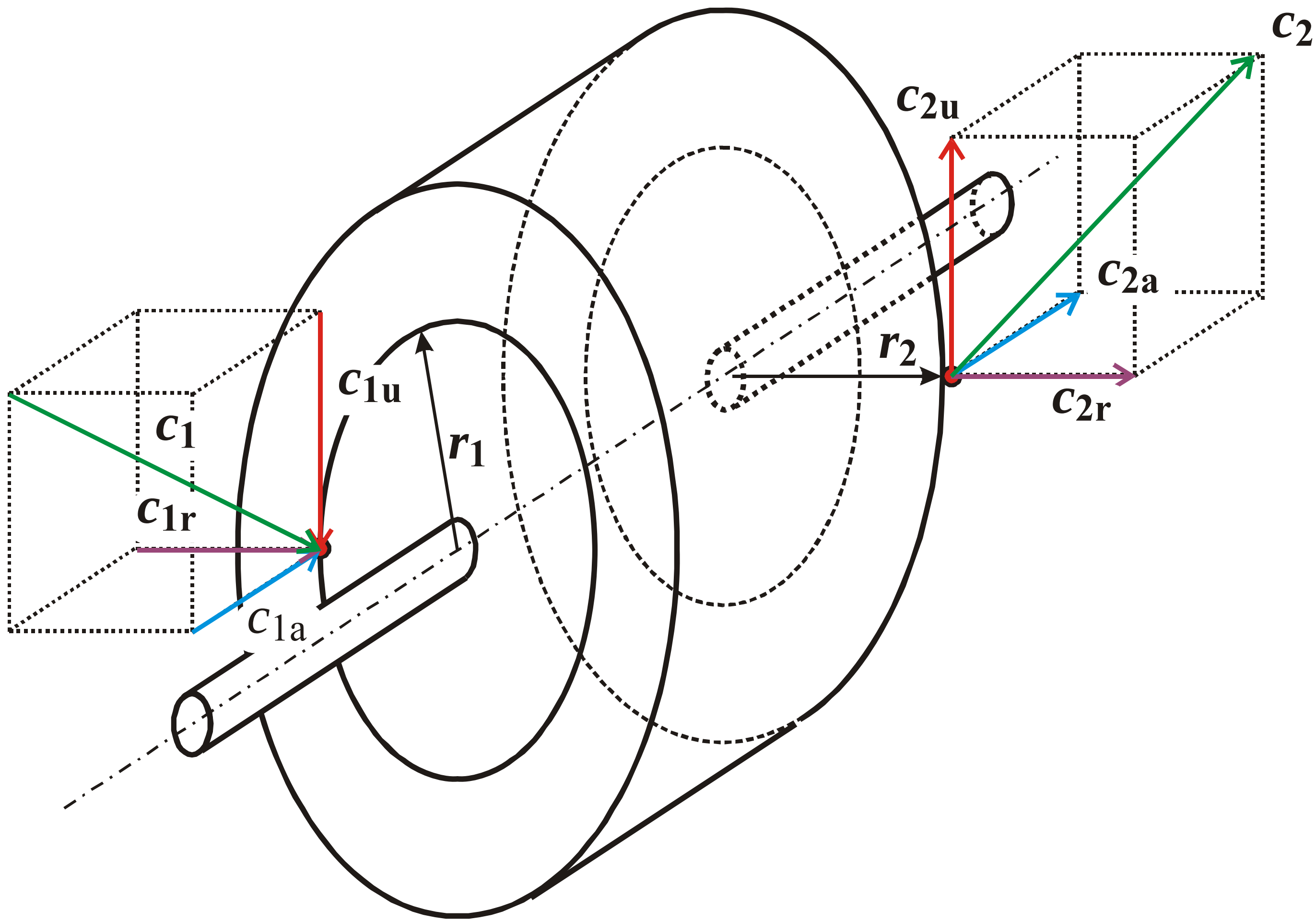
Tok v gonilniku radialnega stroja



Tok v gonilniku aksialnega gonilnika



Hitrostne razmere v gonilniku



Specifično delo gonilnika

$$\frac{P}{\dot{m}} = \frac{W}{m} = y = \int_1^2 u \cdot \mathrm{d}c_\mathrm{u} = c_{2\mathrm{u}} \cdot u_2 - c_{1\mathrm{u}} \cdot u_1$$

$$w^2 = c^2 + u^2 - 2 \cdot u \cdot c_\mathrm{u}$$

$$u \cdot c_u = \frac{c^2 + u^2 - w^2}{2}$$

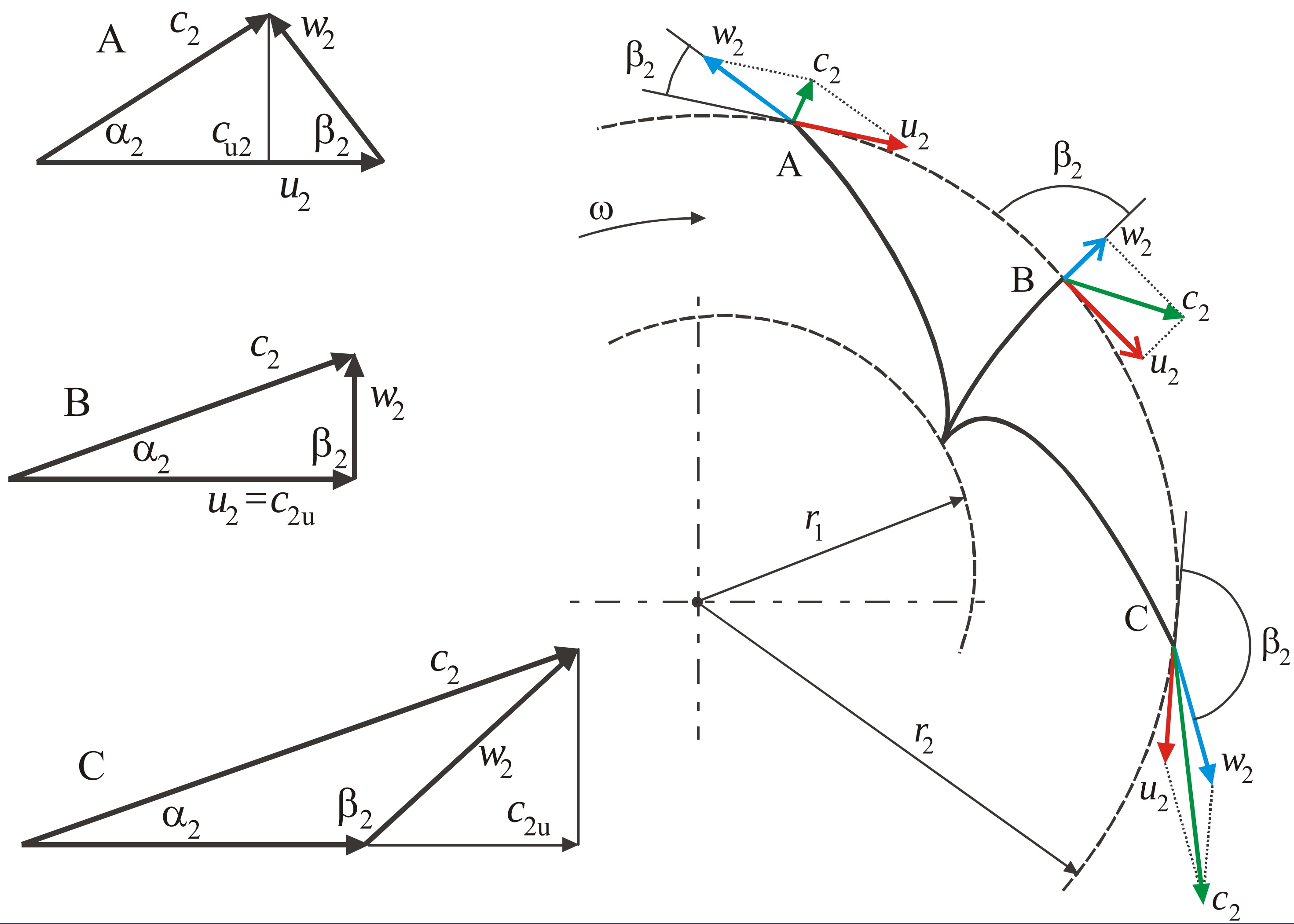
$$y = \frac{\left(c_2^2 - c_1^2\right)}{2} + \frac{\left(u_2^2 - u_1^2\right)}{2} - \frac{\left(w_2^2 - w_1^2\right)}{2}$$

sprememba kinetične energije

sprememba tlačne energije zaradi centrifugalne sile

sprememba tlačne energije spremembe relativne hitrosti

Zakrivljenost lopatic



Zakrivljenost lopatic

Turbinski stroji	$\beta_2 < 90°$	$\beta_2 = 90°$	$\beta_2 > 90°$
Črpalke	$\beta_2 = 20° - 40°$ $\rho = 0{,}5 - 1$		
Vodne turbine	$\beta_2 < 90°$ $\rho = 1$ aksialne (Kaplan)	$\beta_2 = 90°$ $\rho > 0{,}5$ radialne, diag. (Francis)	$\beta_2 = 173° - 175°$ $\rho = 0$ tangencialne (Pelton)
Kompresorji	$\beta_2 = 20° - 40°$ $\rho = 0{,}5 – 1$ aksialni, radialni		
Plinske turbine	$\beta_2 < 90°$ $\rho = 0{,}3 – 0{,}8$ aksialne		
Parne turbine		$\beta_2 = 90°$ $\rho = 0{,}5$ aksialne	$\beta_2 = 155° - 160°$ $\rho = 0$ aksialne

Idealna energijska karakteristika turbinskega stroja

Predpostavke:

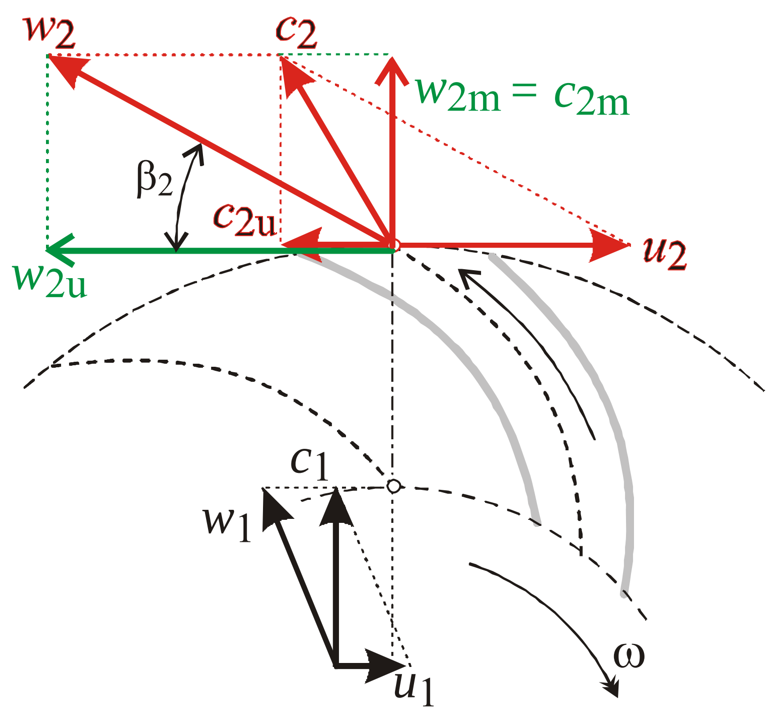
- stacionarno stanje
- poenostavitve za obratovanje v optimalni točki:
  - ni predrotacije
  - prevladujoč vpliv razmer na zunanjem premeru
  - tok v kanalu med lopaticami je regularen – brez izgub

Energijska karakteristika

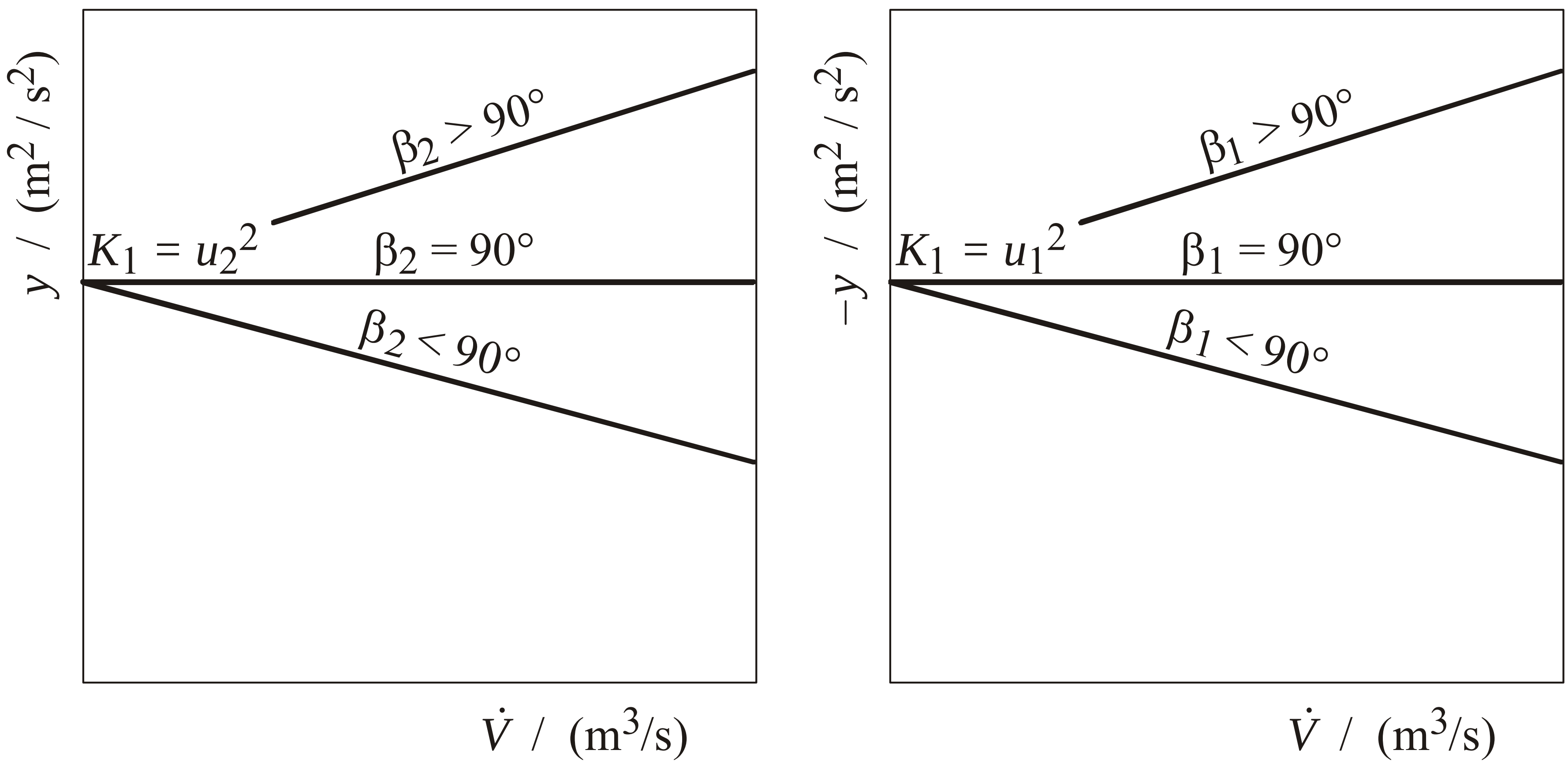
$$y = y(\dot{V})$$

Primer: radialni delovni stroj (črpalka)

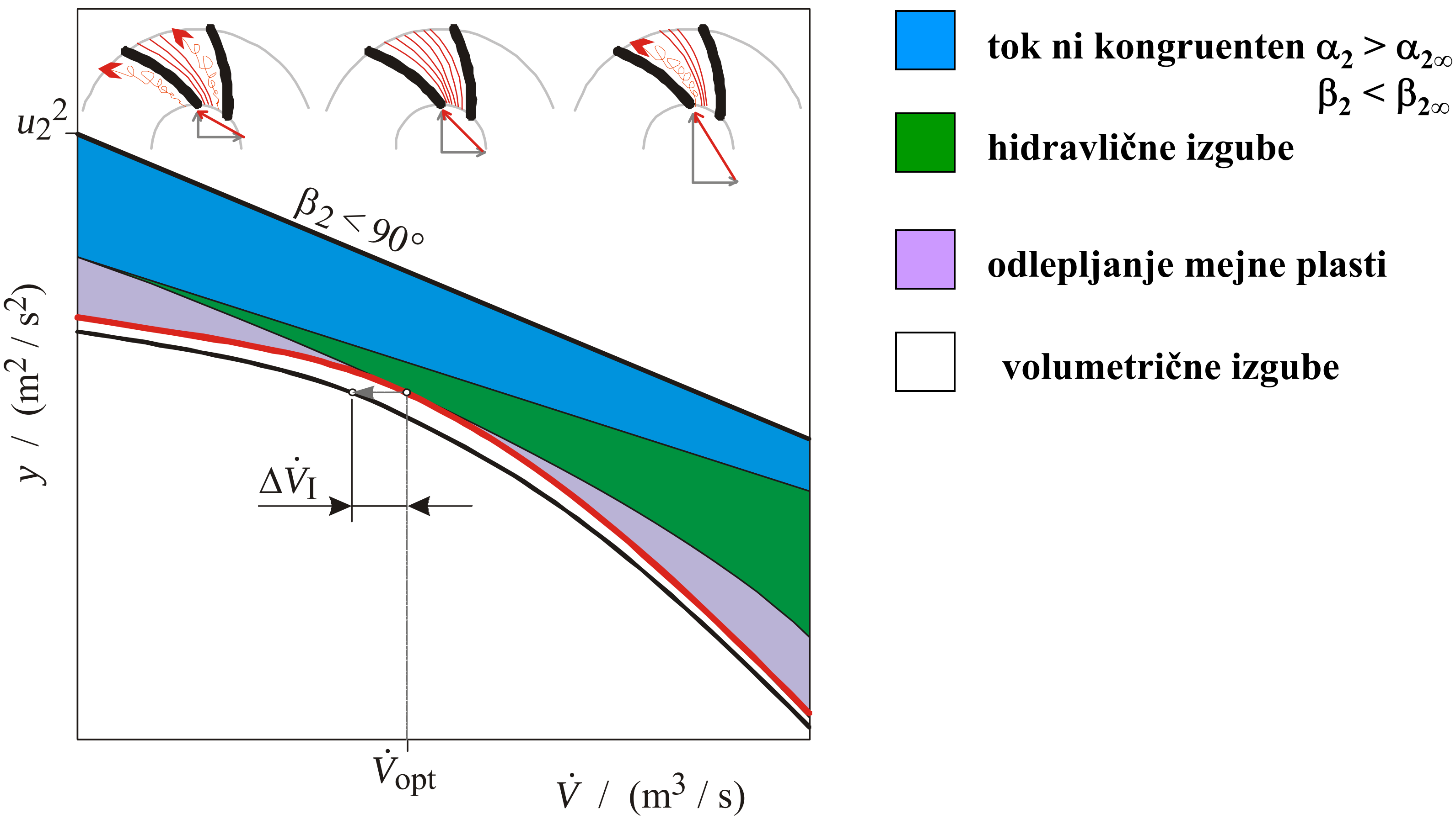
$$y = u_2 \cdot c_{u2} = u_2 \cdot (u_2 - w_{u2})$$



Idealna energijska karakteristika turbinskega stroja



Dejanska karakteristika turbinskega stroja



Podobni stroji

Pretok skozi turbinski stroj

$$\dot{V} = \pi \cdot d \cdot B \cdot c = \\ = \pi \cdot \left(\frac{B}{d}\right) \cdot d \cdot d \cdot \left(\frac{c}{u}\right) \cdot \pi \cdot d \cdot n = \\ = \pi^2 \cdot \left(\frac{B}{d}\right) \cdot \left(\frac{c}{u}\right) \cdot d^3 \cdot n$$

Specifično delo

$$y = u \cdot c_{\mathrm{u}} = \\ = \pi \cdot d \cdot n \cdot \left(\frac{c_{\mathrm{u}}}{u}\right) \cdot \pi \cdot d \cdot n = \\ = \pi^2 \cdot \left(\frac{c_{\mathrm{u}}}{u}\right) \cdot d^2 \cdot n^2$$

Moč

$$P = \rho \cdot \dot{V} \cdot u \cdot c_{\mathrm{u}} = \\ = \rho \cdot \left[\pi^2 \cdot \left(\frac{B}{d}\right) \cdot \left(\frac{c}{u}\right) \cdot d^3 \cdot n\right] \cdot \left[\pi^2 \cdot \left(\frac{c_{\mathrm{u}}}{u}\right) \cdot d^2 \cdot n^2\right] = \\ = \rho \cdot \pi^4 \cdot \left(\frac{B}{d}\right) \cdot \left(\frac{c}{u}\right) \cdot \left(\frac{c_{\mathrm{u}}}{u}\right) \cdot d^5 \cdot n^3$$

Zakoni podobnosti

$$\frac{\dot{V}_{\mathrm{I}}}{\dot{V}_{\mathrm{M}}} = \frac{n_{\mathrm{I}}}{n_{\mathrm{M}}} \cdot \left(\frac{d_{\mathrm{I}}}{d_{\mathrm{M}}}\right)^{3}$$

$$\frac{y_{\mathrm{I}}}{y_{\mathrm{M}}} = \frac{H_{\mathrm{I}}}{H_{\mathrm{M}}} = \left(\frac{n_{\mathrm{I}}}{n_{\mathrm{M}}}\right)^{2} \cdot \left(\frac{d_{\mathrm{I}}}{d_{\mathrm{M}}}\right)^{2}$$

$$\frac{P_{\mathrm{I}}}{P_{\mathrm{M}}} = \left(\frac{\rho_{\mathrm{I}}}{\rho_{\mathrm{M}}}\right) \cdot \left(\frac{n_{\mathrm{I}}}{n_{\mathrm{M}}}\right)^{3} \cdot \left(\frac{d_{\mathrm{I}}}{d_{\mathrm{M}}}\right)^{5}$$

Značilna vrtilna frekvenca

Z energijskim in pretočnim številom tvorimo nov brezdimenzijski parameter

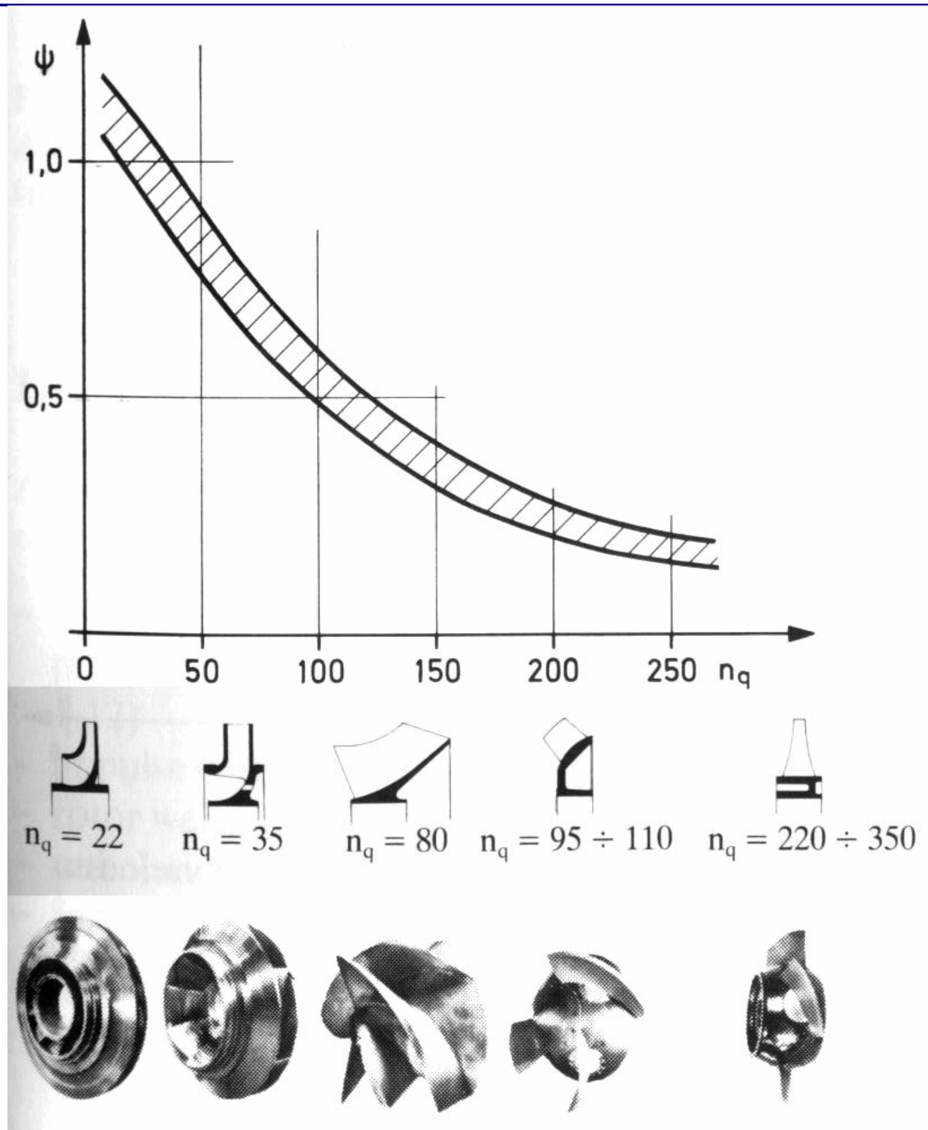
$$n_q^* = \frac{\varphi^{\frac{1}{2}}}{\psi^{\frac{3}{4}}} \cdot \frac{1}{\left(2 \cdot \pi^2\right)^{\frac{1}{4}}} = \frac{n \cdot \dot{V}^{\frac{1}{2}}}{y^{\frac{3}{4}}}$$

$$n_q = \frac{n \cdot \dot{V}^{\frac{1}{2}}}{H^{\frac{3}{4}}}$$

ima enoto, vrtilne frekvence

Spec. vrtilna frekvenca pove, kolikšno vrtilno frekvenco bi imel turbinski stroj v točki optimalnega izkoristka pri pretoku 1 m3/s in bi imel dobavno višino 1 m.

Pretočno število



Cordierjev diagram

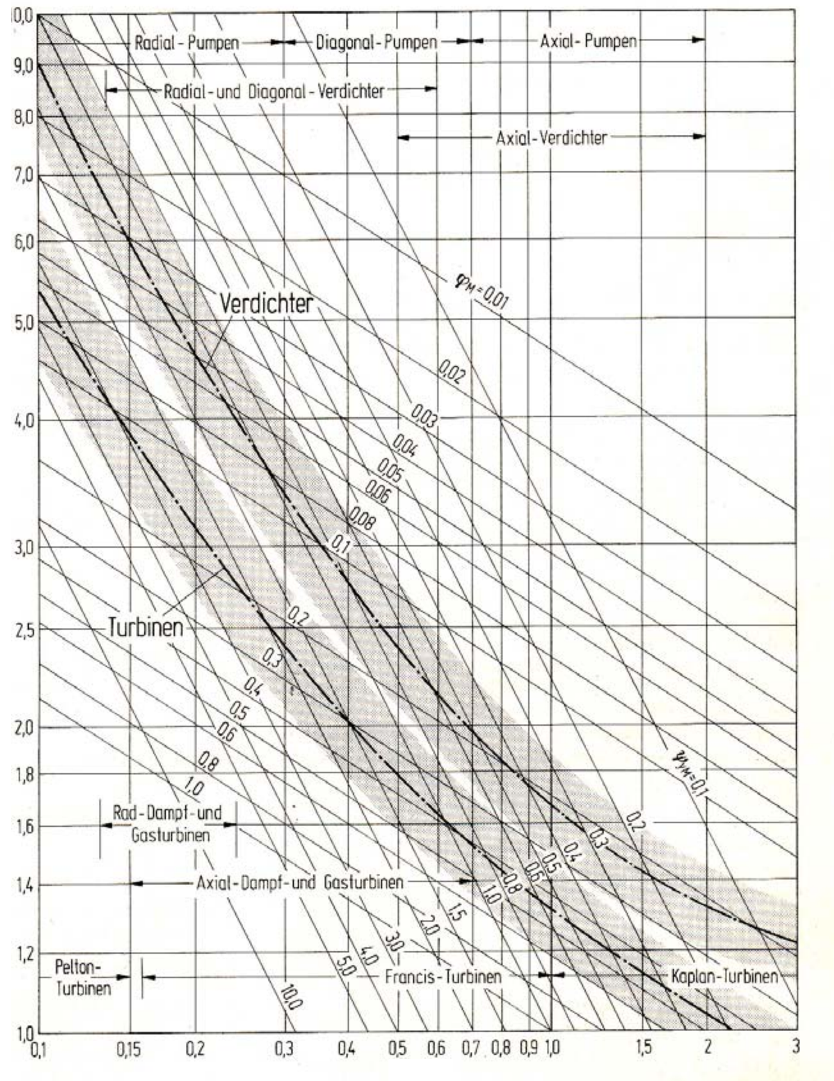
Značilna vrtilna frekvenca

$$\sigma = \frac{\varphi^{1/2}}{\psi^{3/4}} = \left(2 \cdot \pi^2\right)^{1/4} \cdot \frac{n \cdot \dot{V}^{1/2}}{y^{3/4}}$$

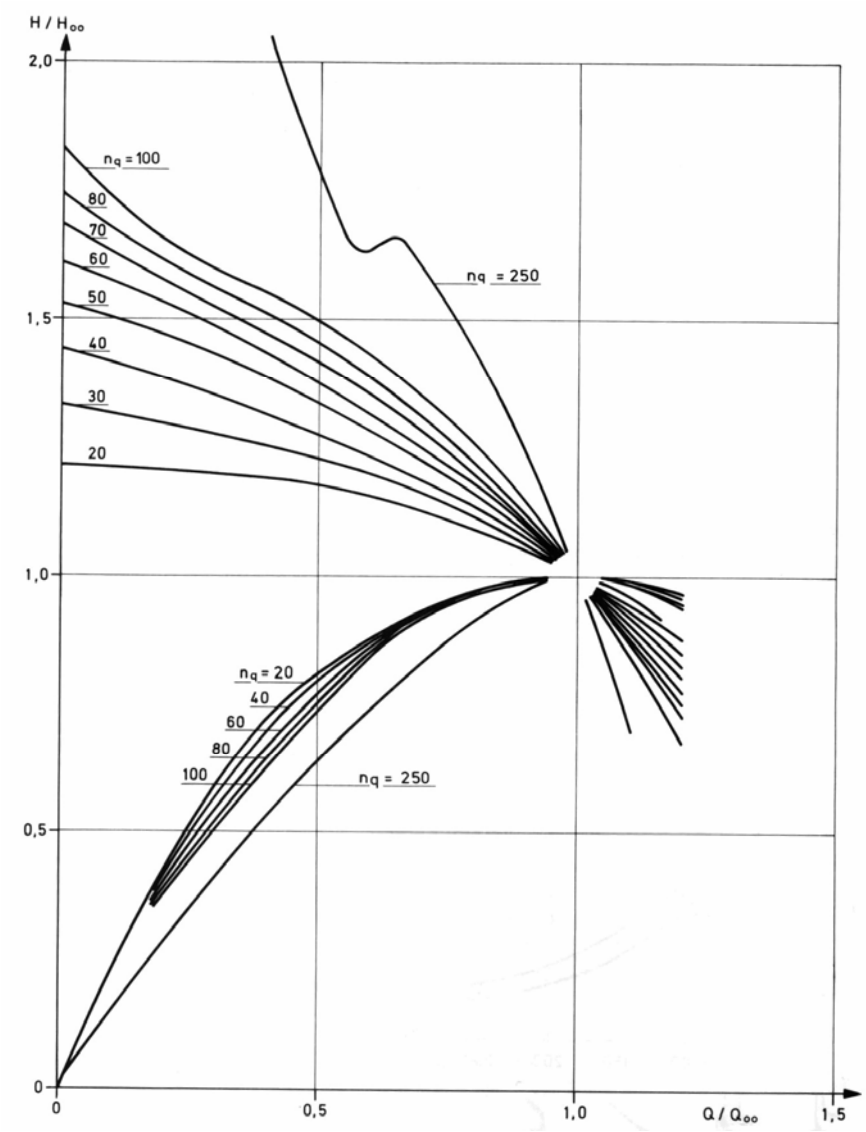
Značilni premer

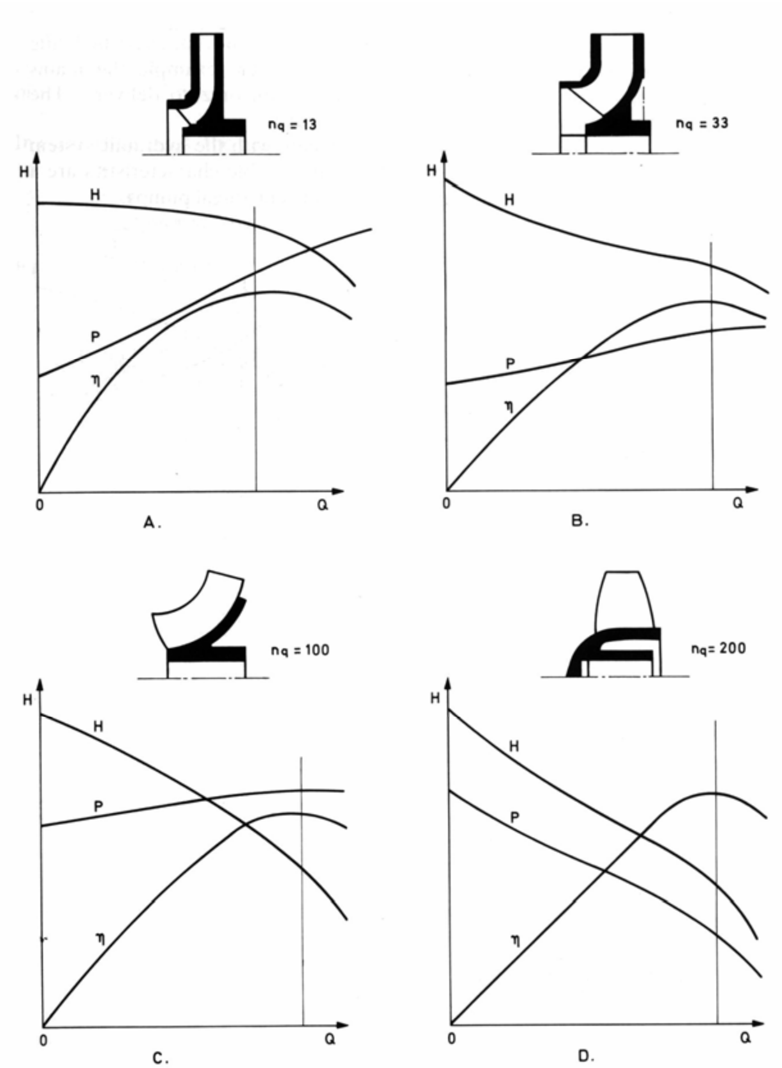
$$\delta = \frac{\psi^{1/4}}{\varphi^{1/2}} = \left(\frac{\pi^2}{8}\right)^{1/4} \cdot \frac{d \cdot y^{1/4}}{\dot{V}^{1/2}}$$

δ



σ


H / Hoo
2,0
1,5
1,0
0,5
0
nq = 100
80
70
60
50
40
30
20
nq = 250
nq = 20
40
60
80
100
nq = 250
0
0,5
1,0
Q / Qoo
1,5


nq = 13
H
H
P
η
0
Q
A.
nq = 33
H
H
P
η
0
Q
B.
nq = 100
H
H
P
η
0
Q
C.
nq= 200
H
H
P
η
0
Q
D.

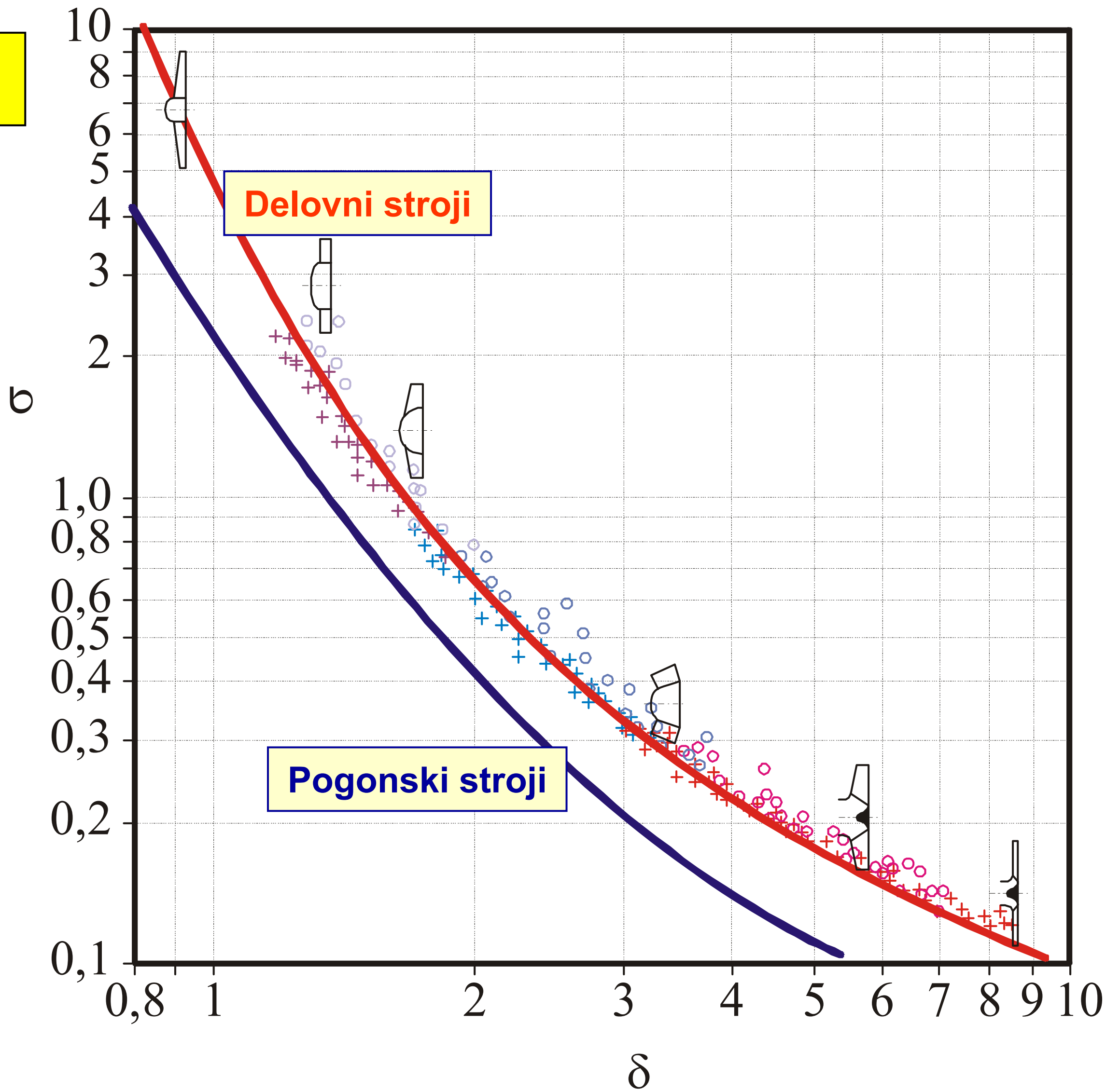
Cordierjev diagram

Značilna vrtilna frekvenca

$$\sigma = \frac{\varphi^{1/2}}{\psi^{3/4}} = \left(2 \cdot \pi^2\right)^{1/4} \cdot \frac{n \cdot \dot{V}^{1/2}}{y^{3/4}}$$

Značilni premer

$$\delta = \frac{\psi^{1/4}}{\varphi^{1/2}} = \left(\frac{\pi^2}{8}\right)^{1/4} \cdot \frac{d \cdot y^{1/4}}{\dot{V}^{1/2}}$$



Cordierjev diagram

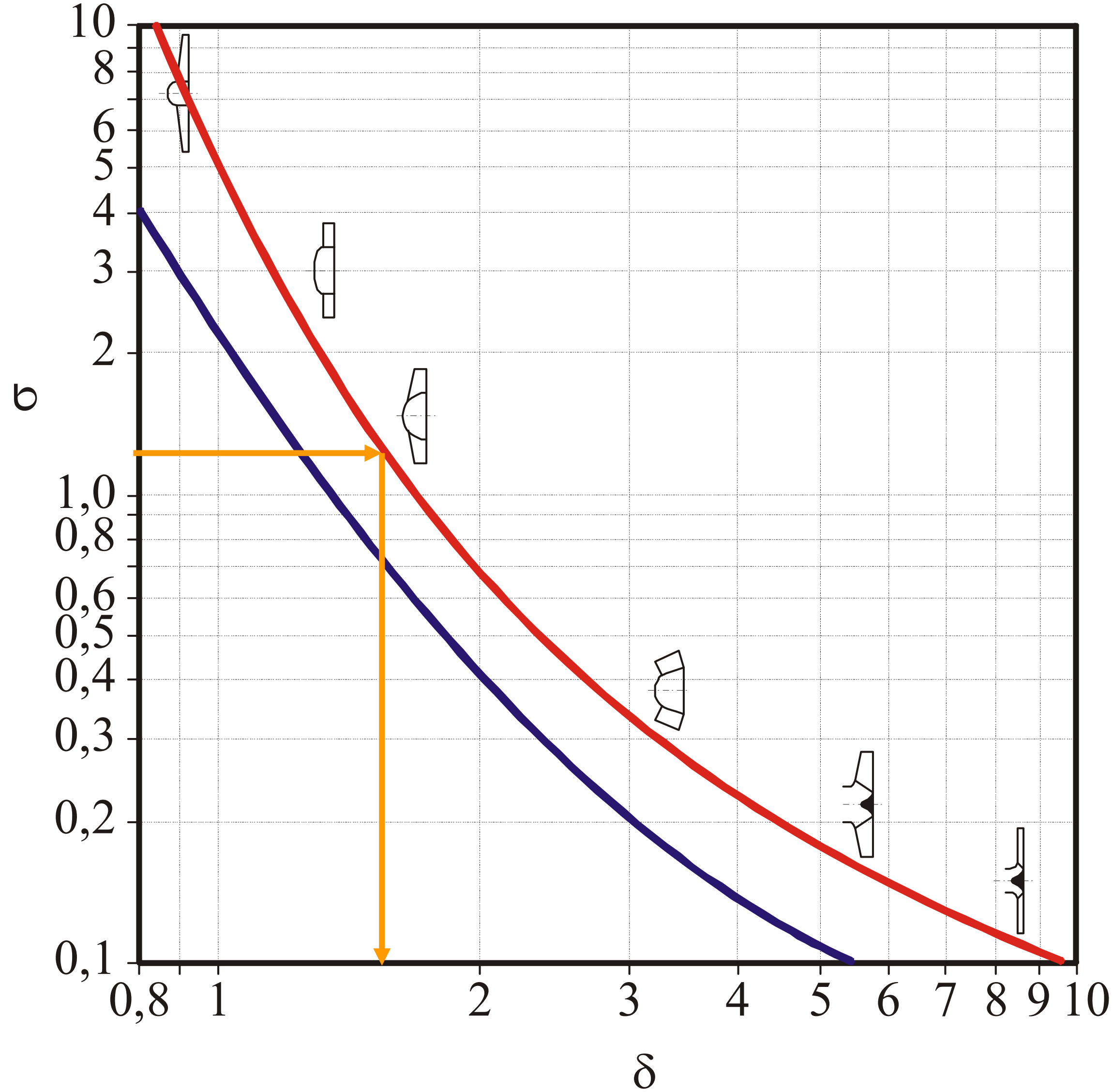
Primer uporabe:
Pri projektiranju novih strojev
Poznamo: $\dot{V}$, y in n

1. $$\sigma = \left(2 \cdot \pi^2\right)^{1/4} \cdot \frac{n \cdot \dot{V}^{1/2}}{y^{3/4}}$$

2. $\delta \rightarrow \delta(\sigma)$ Cordierjev diagram

3. Hidravlična oblika rotorja

4. $$d = \left(\frac{\pi^2}{8}\right)^{1/4} \cdot \frac{\dot{V}^{1/2}}{\delta \cdot y^{1/4}}$$



Cordierjev diagram

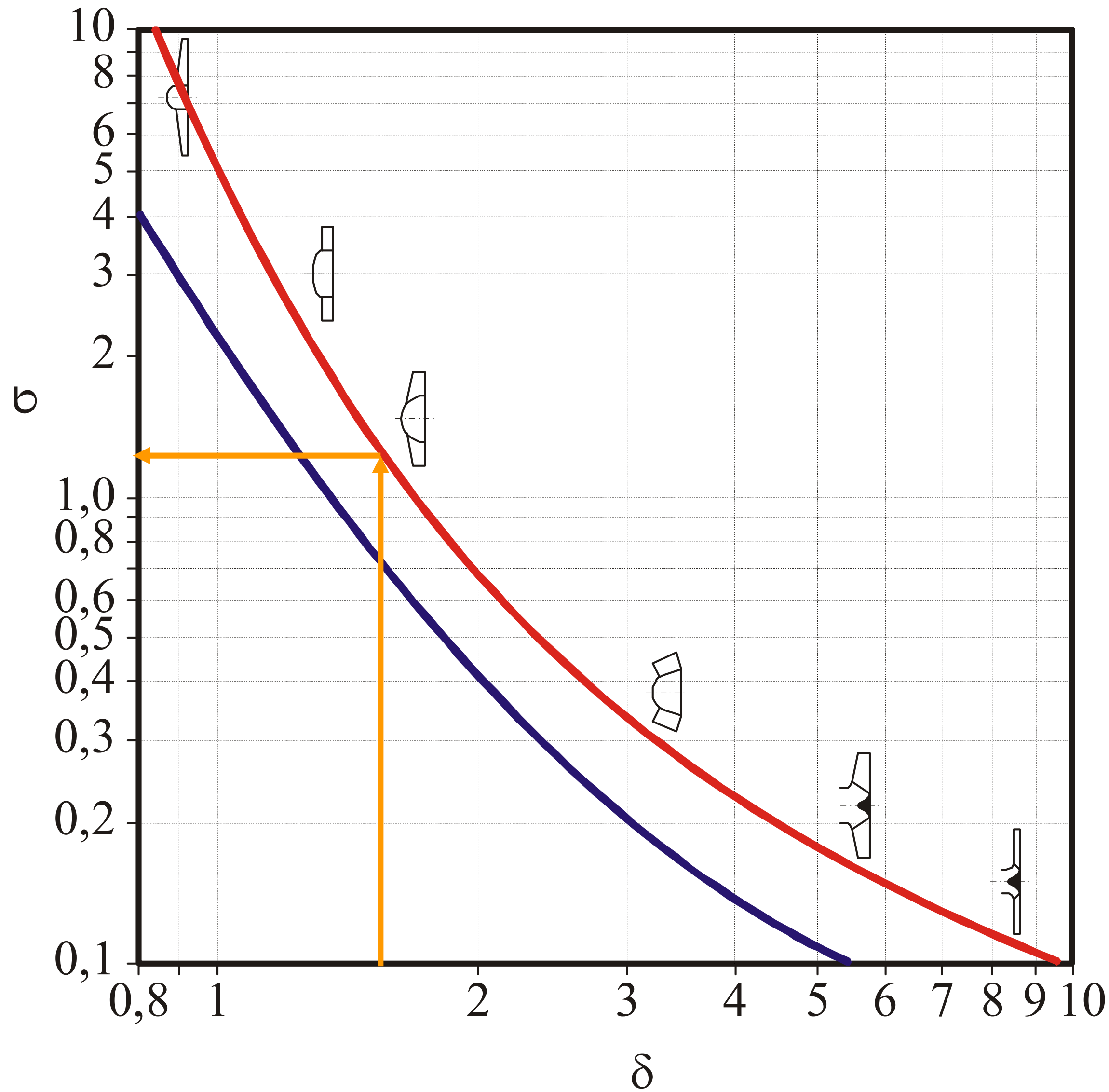
Primer uporabe:
Pri projektiranju novih strojev
Poznamo: D, y in $\dot{V}$

1. $$\delta = \left(\frac{\pi^2}{8}\right)^{1/4} \cdot \frac{d \cdot y^{1/4}}{\dot{V}^{1/2}}$$

2. $\sigma \rightarrow \sigma(\delta)$ Cordierjev diagram

3. Hidravlična oblika rotorja

4. $$n = \left(2 \cdot \pi^2\right)^{1/4} \cdot \frac{y^{3/4}}{\sigma \cdot \dot{V}^{1/2}}$$



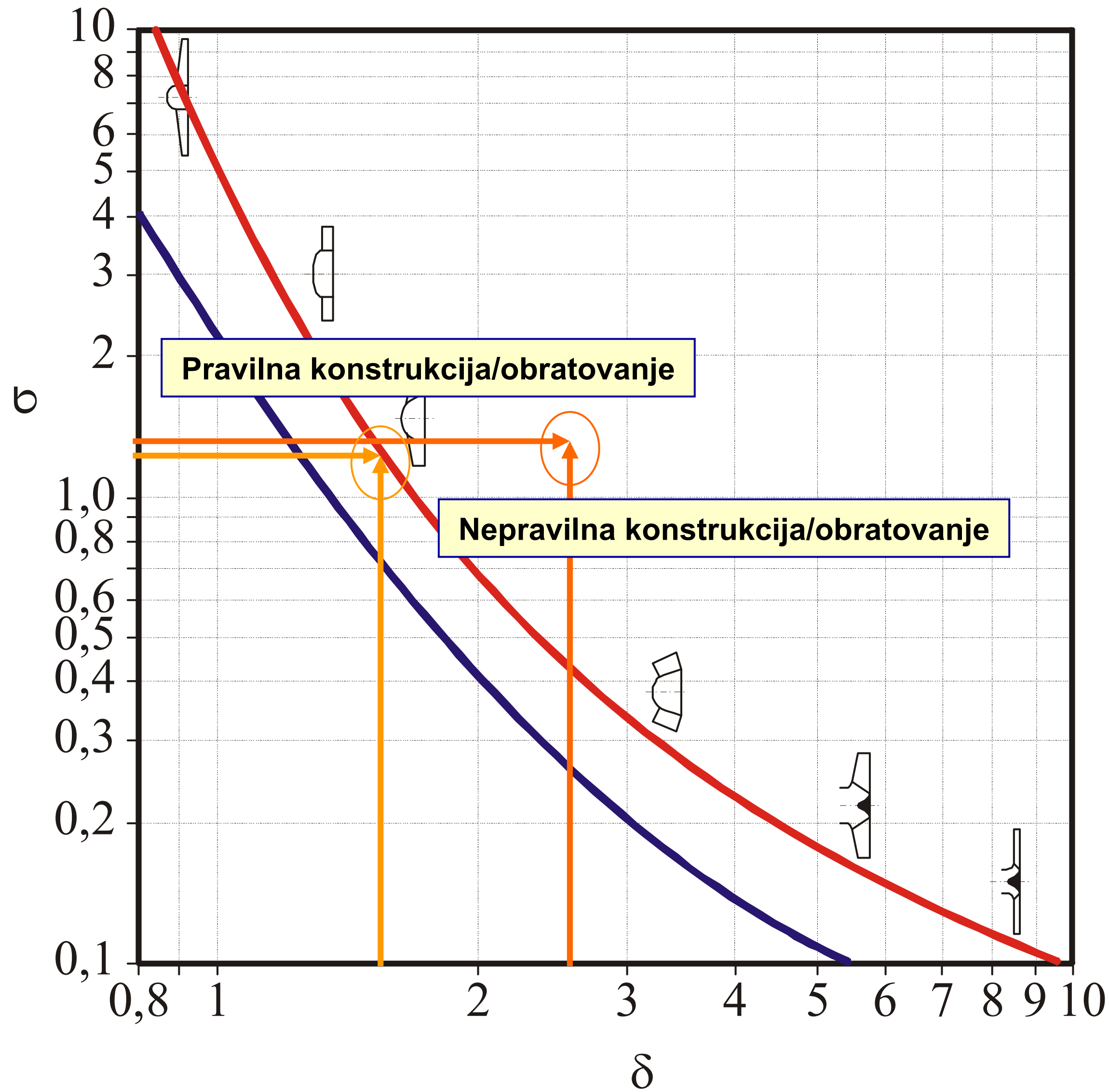
Cordierjev diagram

Primer uporabe:
Poznamo vse veličine:
$\dot{V}$, D, y in n

Izračunamo par:

σ, δ

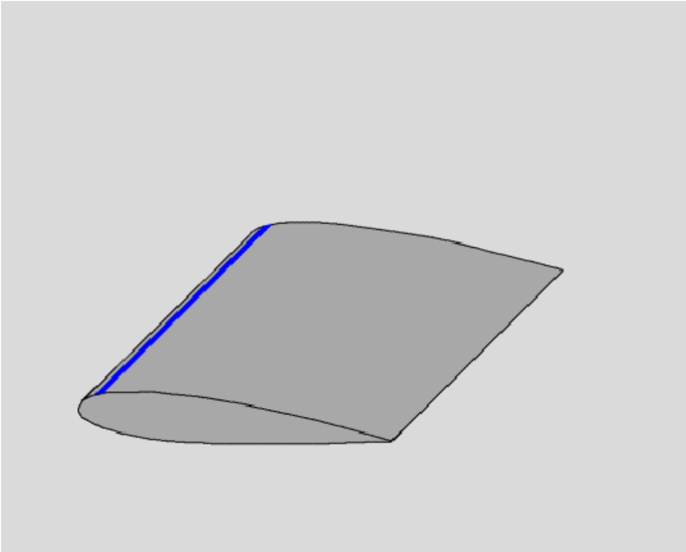
Kontrola konstrukcije in obratovanja

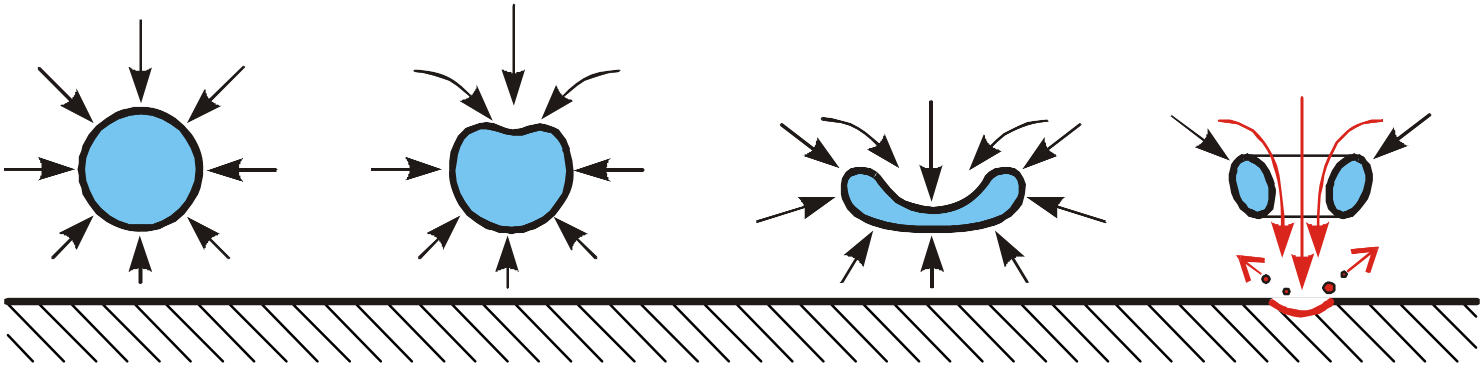


Kavitacija

Kavitacijsko število

$$Ka = \frac{p - p'(T)}{\frac{\rho \cdot v^2}{2}}$$





Črpalke

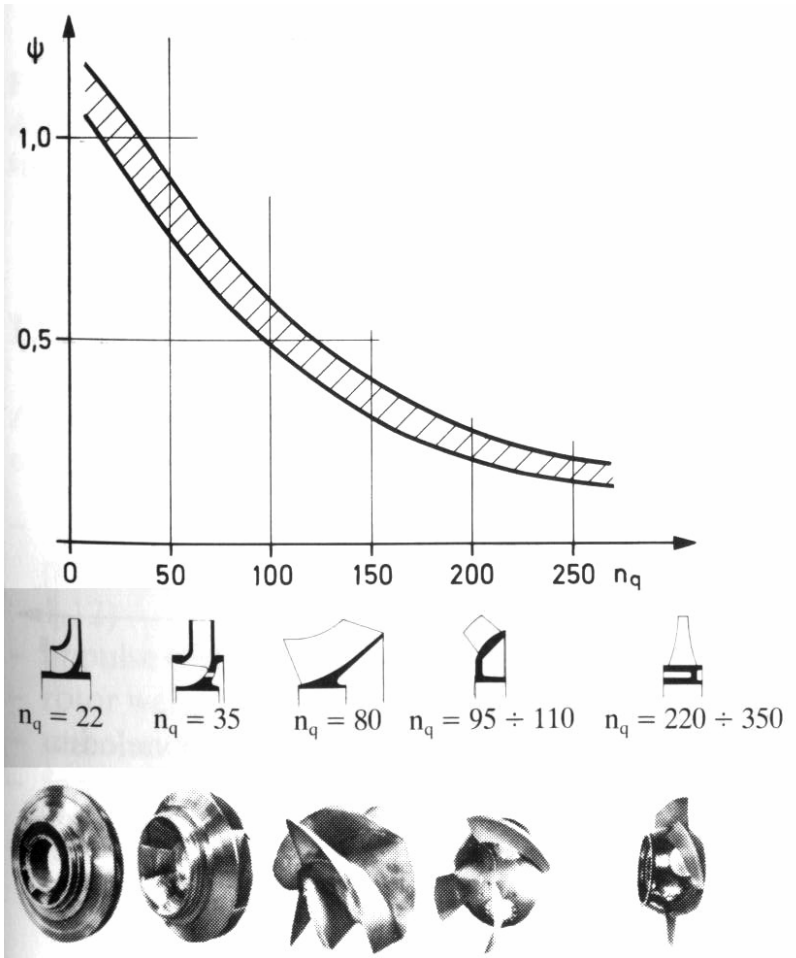
Razdelitev in uporaba

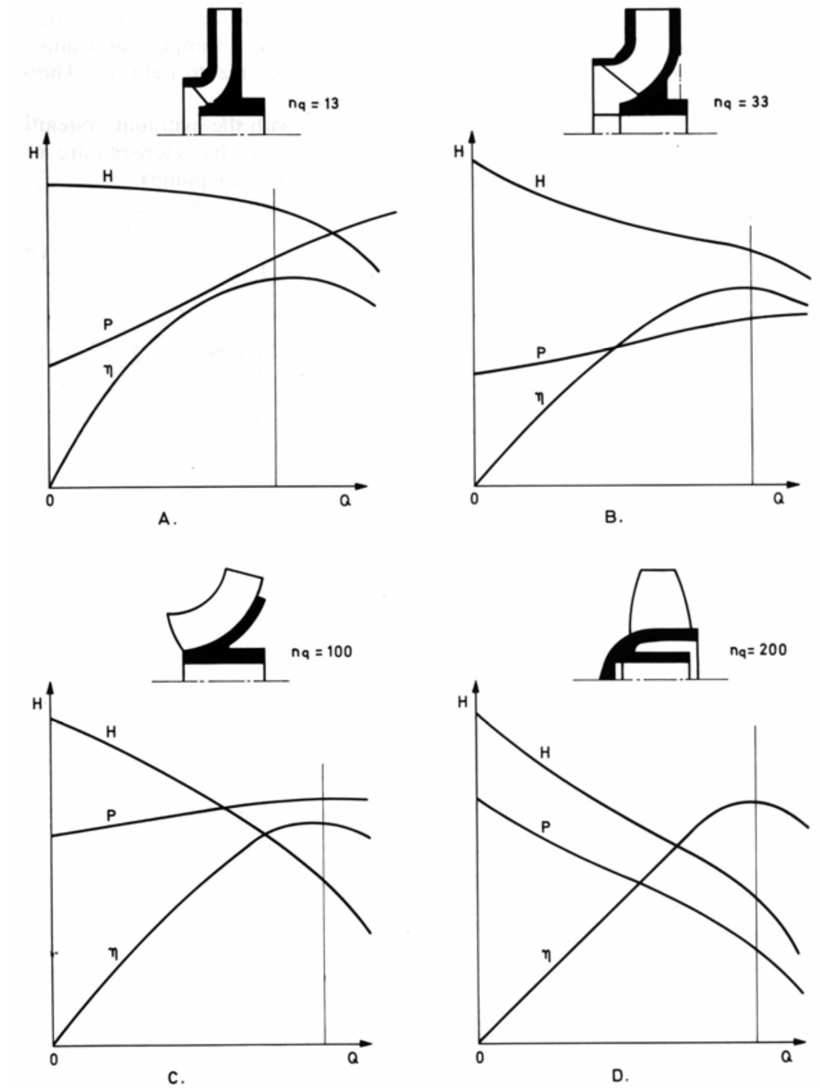
Delo, moč in izkoristek

Energijska karakteristika

Regulacija

Razdelitev in uporaba





Delo, moč in izkoristek

Izentropa se ujema z izohoro: $\rho = konst.$

$$W_{\mathrm{t\check{C}}} = V \cdot \left(p_2 - p_1 \right) = m \cdot \frac{p_2 - p_1}{\rho} = m \cdot \frac{\Delta p_{\mathrm{\check{C}}}}{\rho} = m \cdot g \cdot \Delta H_{\mathrm{\check{C}}}$$

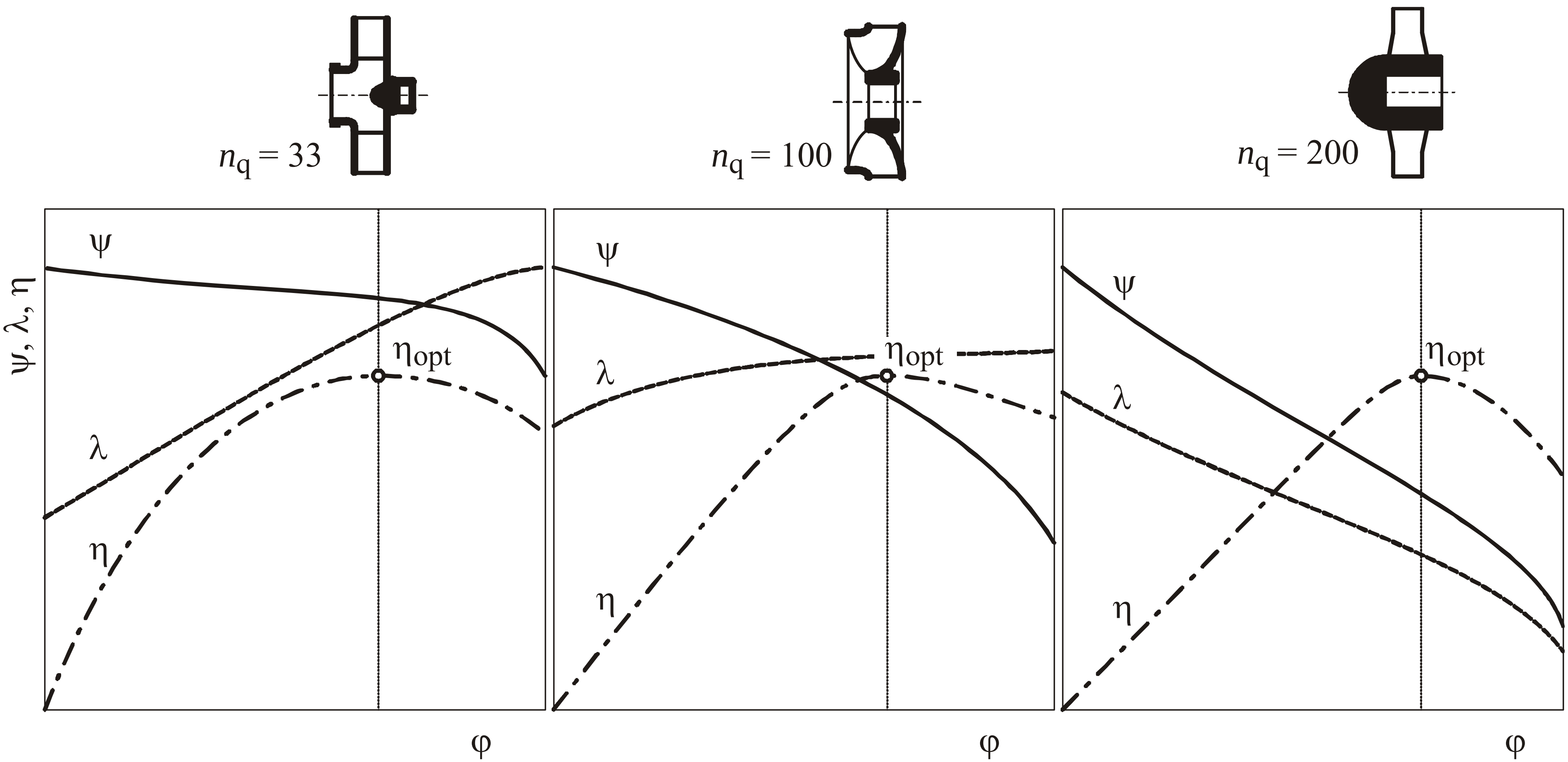
Dobavna višina

$$W_{\mathrm{t\check{C}}} = W_{\mathrm{tC}} = m \cdot g \cdot \Delta H_{\mathrm{C}} = \left[\frac{p_\alpha - p_\omega}{\rho \cdot g} + \frac{v_\alpha - v_\omega}{2 \cdot g} + \left(H_\alpha - H_\omega \right) + \sum \Delta H_{\mathrm{I}} \right]$$

$$\eta_{\mathrm{e}} = \frac{W_{\mathrm{t\check{C}}}}{W_{\mathrm{e\check{C}}}} \Rightarrow W_{\mathrm{e\check{C}}} = \frac{m}{\eta_{\mathrm{e}}} \cdot g \cdot \Delta H_{\mathrm{\check{C}}}$$

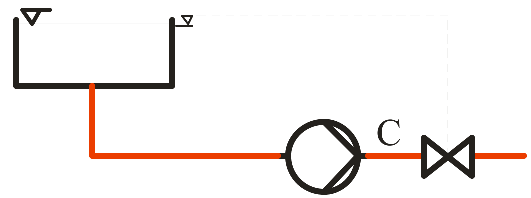
$$P_{\mathrm{e\check{C}}} = \frac{\dot{m} \cdot \Delta p}{\eta_{\mathrm{e}} \cdot \rho} = \frac{\dot{V} \cdot \Delta p}{\eta_{\mathrm{e}}} = \frac{\dot{m} \cdot g \cdot \Delta H}{\eta_{\mathrm{e}}}$$

Energijska karakteristika

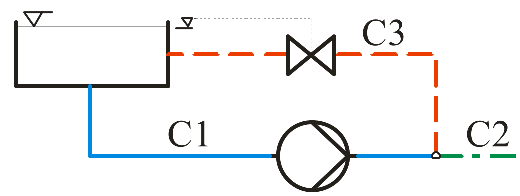


Regulacija

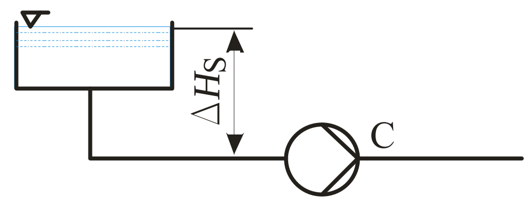
z dušenjem



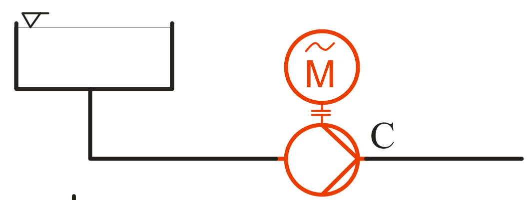
z obvodom



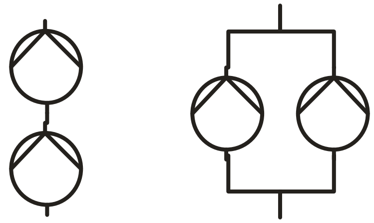
kavitacijska



s spreminjanjem vrtilne frekvence



podvojitev črpalk



Kompresorji

Razdelitev in uporaba

Delo, moč in izkoristek

Energijske karakteristike

Regulacija

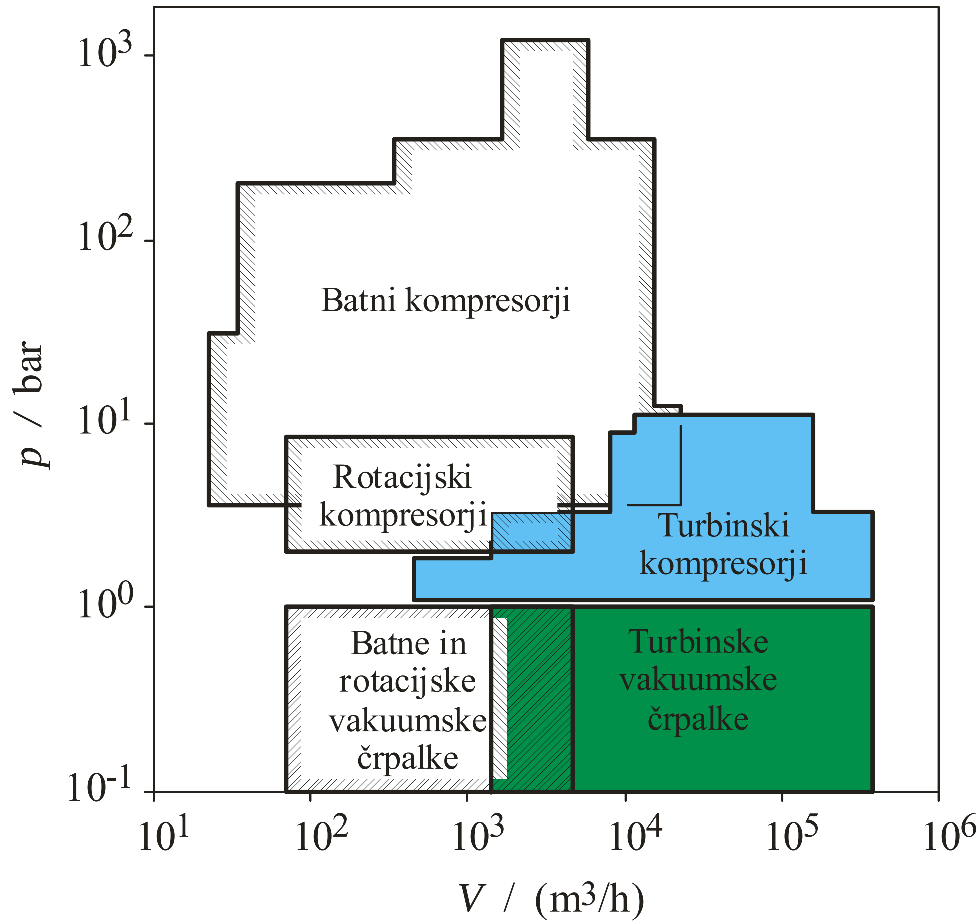
Razdelitev in uporaba

Vakuumske črpalke: $< p_{atm}$

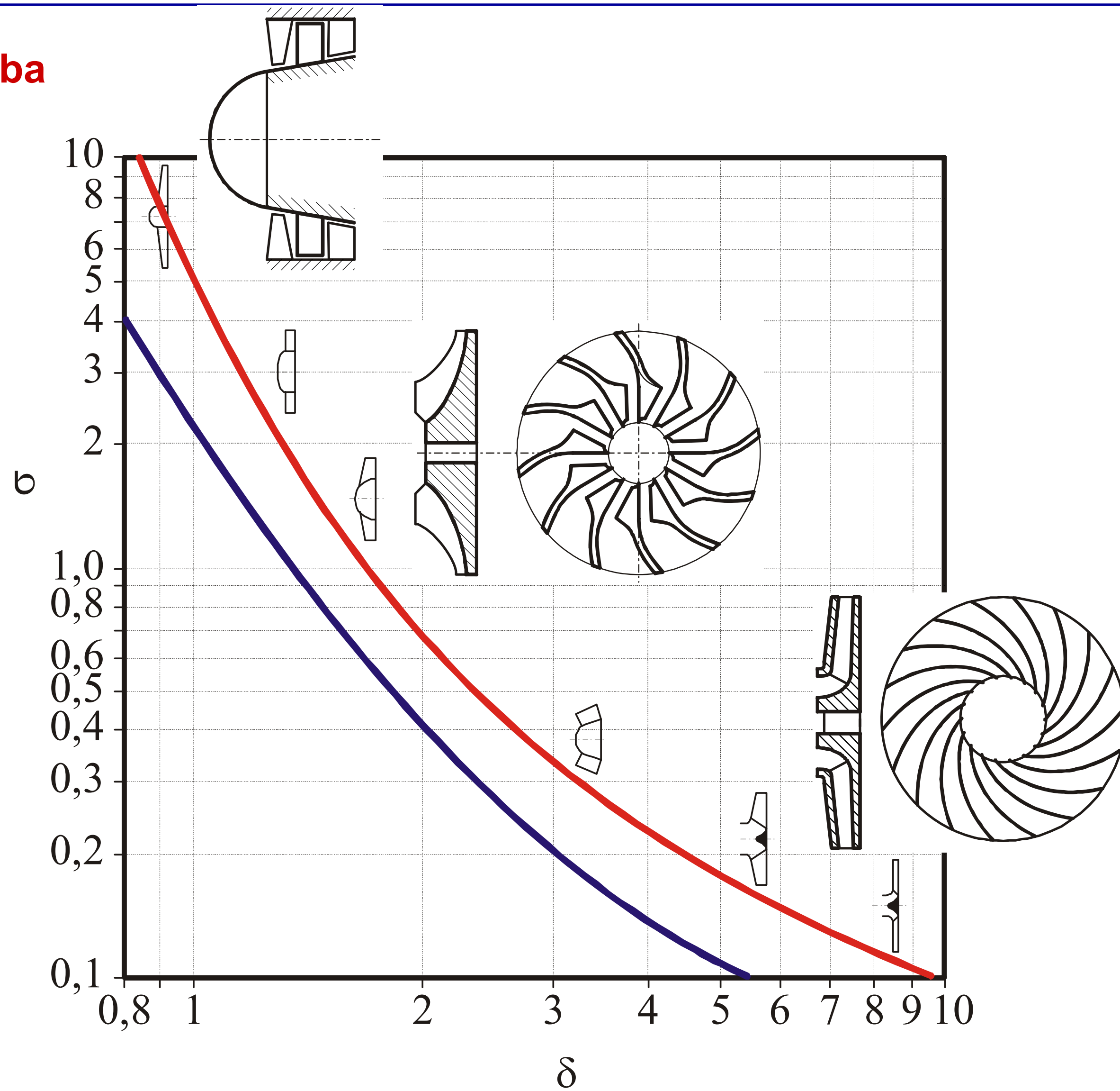
Ventilatorji: $p_{atm} < p < 1{,}1$ bar

Puhala: $1{,}1 < p < 3$ bar

Kompresorji: $p > 3$ bar



Razdelitev in uporaba



Delo, moč in izkoristek

Tehnično delo pri izotermni kompresiji

$$W_\mathrm{t} = p_1 \cdot V_1 \cdot \ln \frac{p_2}{p_1} = m \cdot R \cdot T_1 \cdot \ln \frac{p_2}{p_1}$$

Škodljivega volumna ni!

Tehnično delo pri izentropni kompresiji

$$W_\mathrm{t} = \frac{\kappa}{\kappa - 1} \cdot p_1 \cdot V_1 \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right] = \frac{\kappa}{\kappa - 1} \cdot m \cdot R \cdot T_1 \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right]$$

$$W_\mathrm{t} = m \cdot g \cdot \left(\frac{u_\omega}{g} - \frac{u_\alpha}{g} + \frac{p_\omega}{\rho_\omega \cdot g} - \frac{p_\alpha}{\rho_\alpha \cdot g} + \sum \Delta H_\mathrm{I} \right) = m \cdot (h_\omega - h_\alpha) + g \cdot \sum \Delta H_\mathrm{I}$$

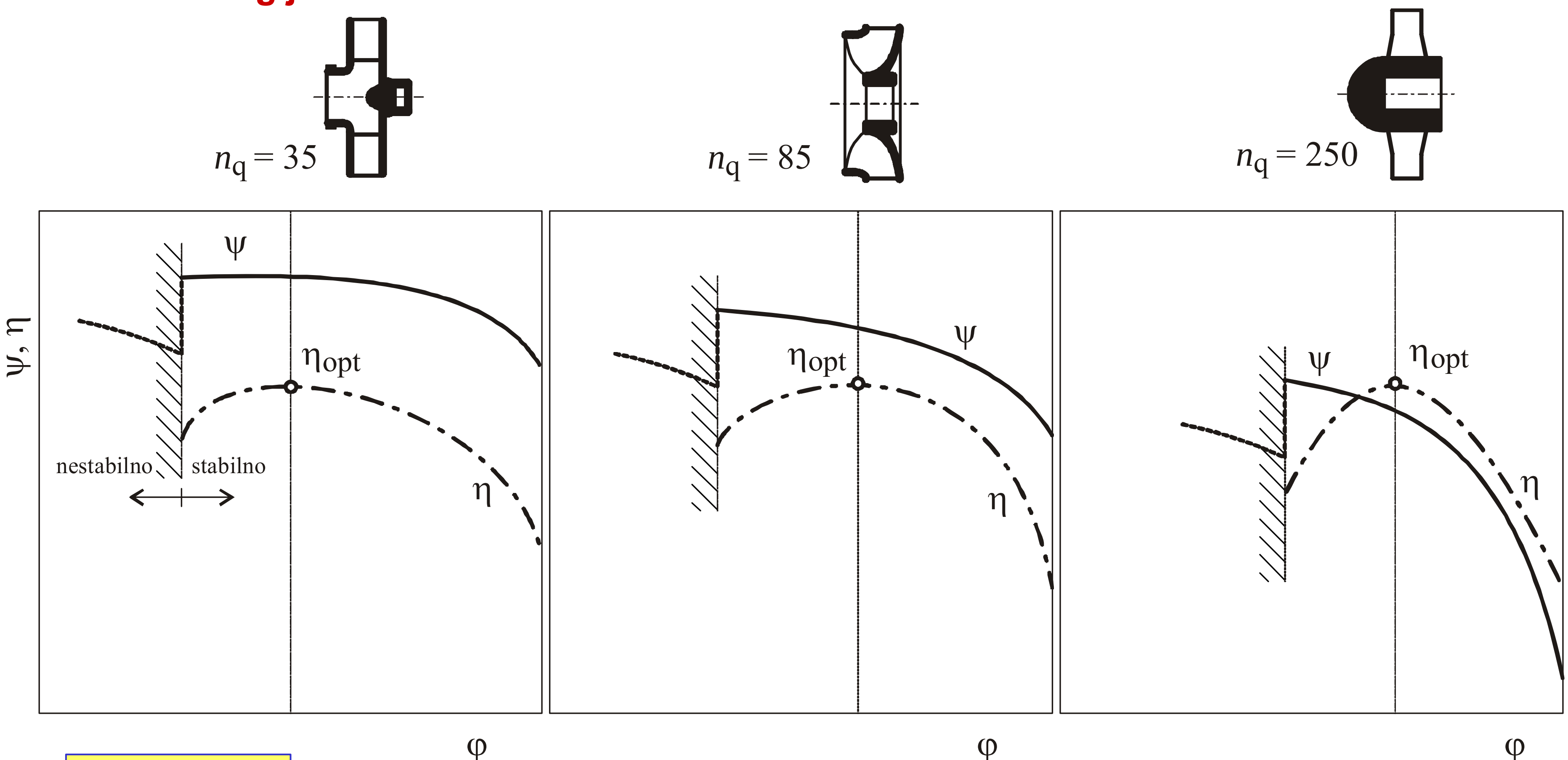
$$W_\mathrm{e} = \frac{W_\mathrm{t}}{\eta_\mathrm{e}}$$

$$P_\mathrm{eK} = \frac{\dot{m} \cdot \Delta p}{\eta_\mathrm{e} \cdot \rho} = \frac{\dot{V} \cdot \Delta p}{\eta_\mathrm{e}} = \frac{\dot{m} \cdot g \cdot \Delta H}{\eta_\mathrm{e}} = \frac{\rho \cdot \dot{V} \cdot g \cdot \Delta H}{\eta_\mathrm{e}}$$

$$\frac{p_2}{p_1} = \sqrt[i]{\frac{p_\omega}{p_\alpha}}$$

Optimalno tlačno razmerje pri večstopenjski kompresiji

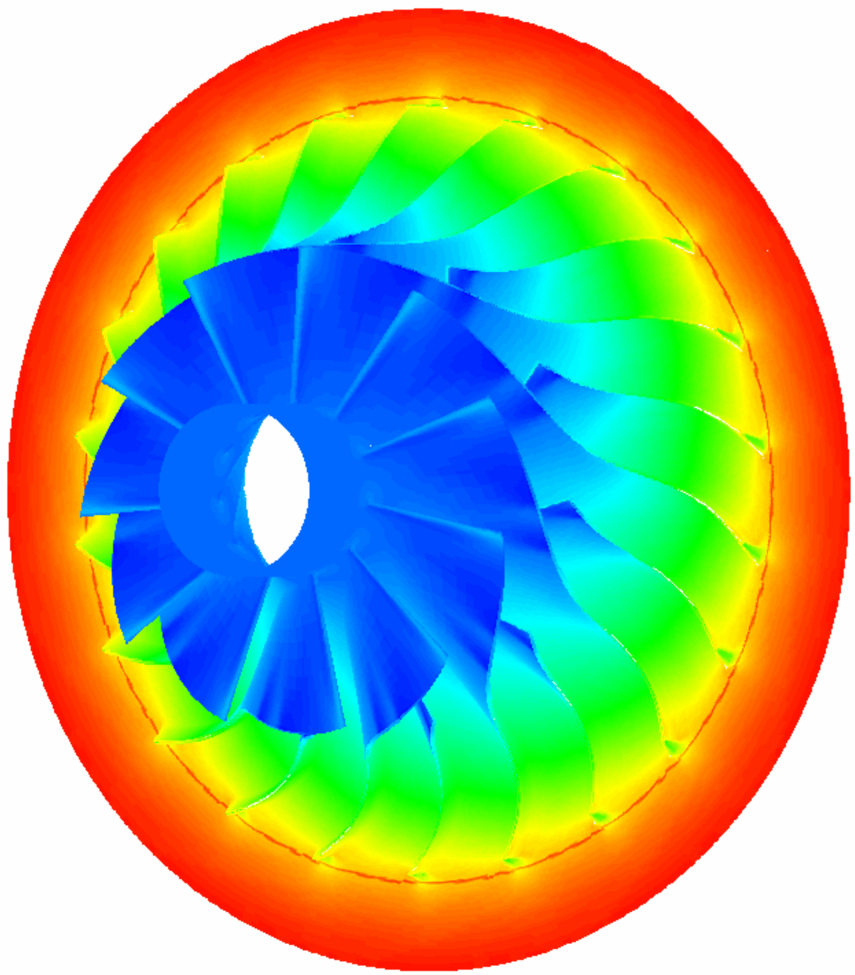
Energijske karakteristike



$$\varphi = \frac{\dot{m} \cdot \sqrt{RT_1}}{p_1 \cdot d^2}$$

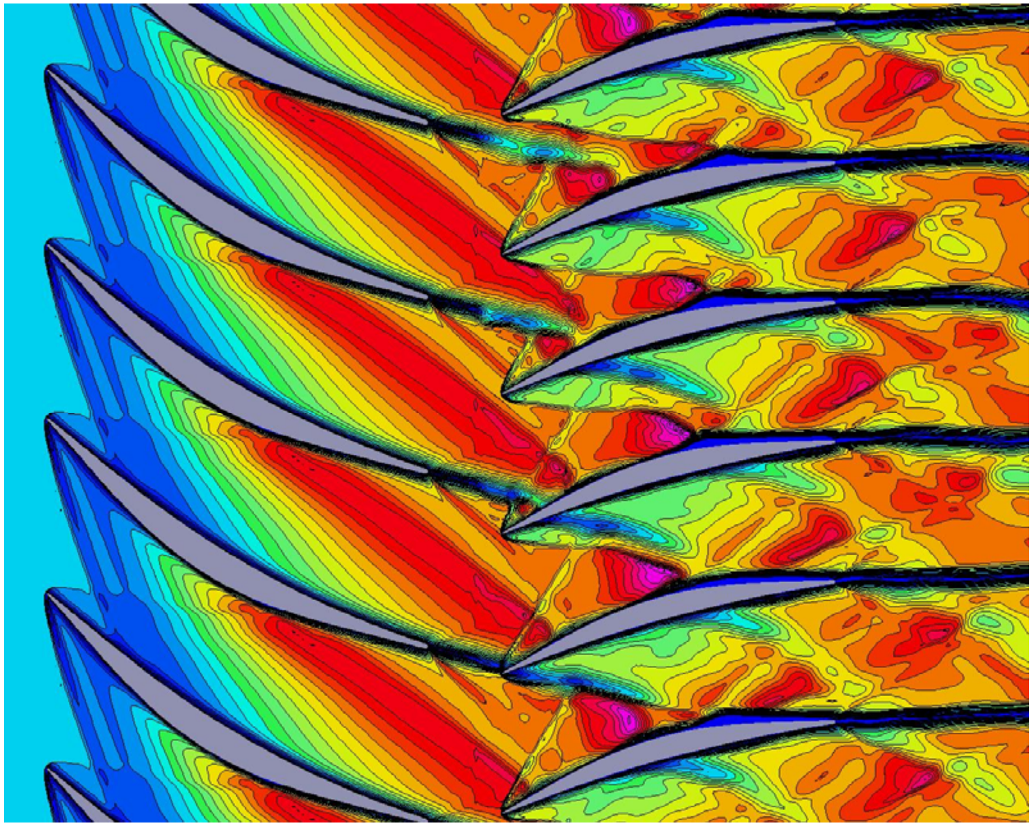
$$\psi = \frac{p_2}{p_1}$$

TURBOKOMPRESORJI



Gonilnik radialnega kompresorja

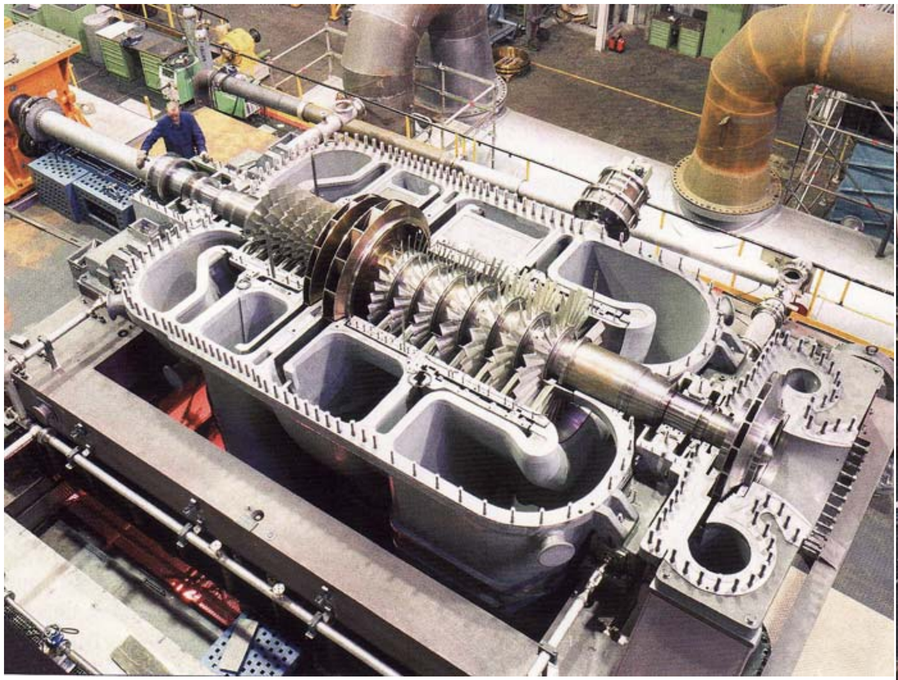
TURBOKOMPRESORJI

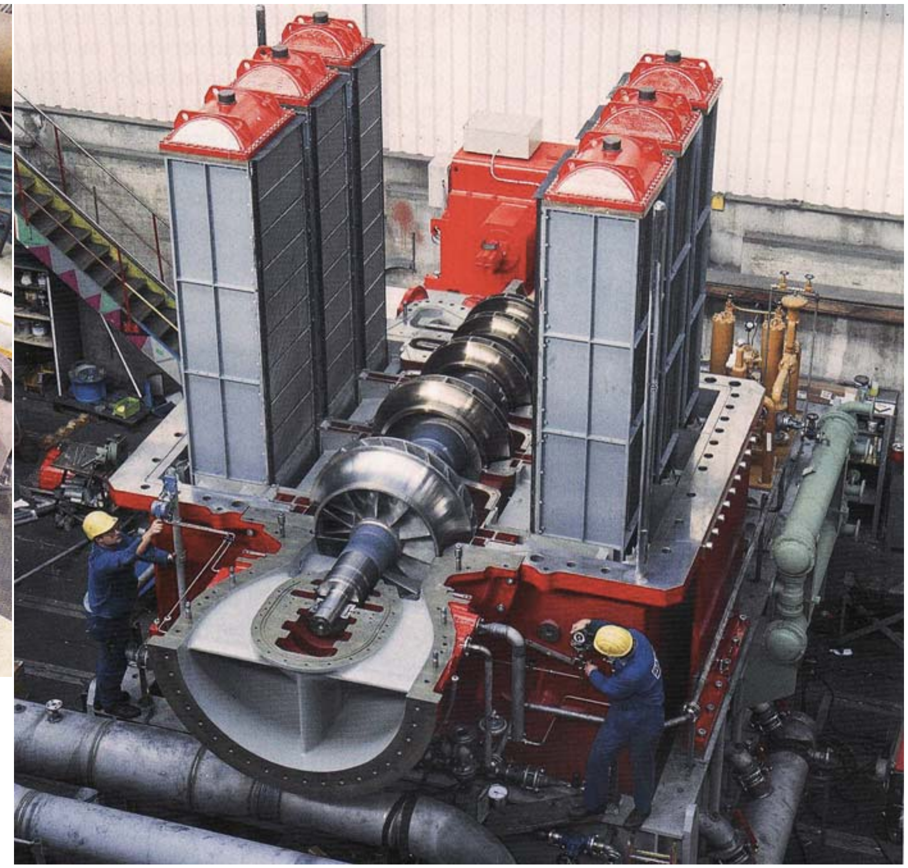


Aksialna kompresorska stopnja nestacionarno tlačno polje

TURBOKOMPRESORJI

Večstopenjski

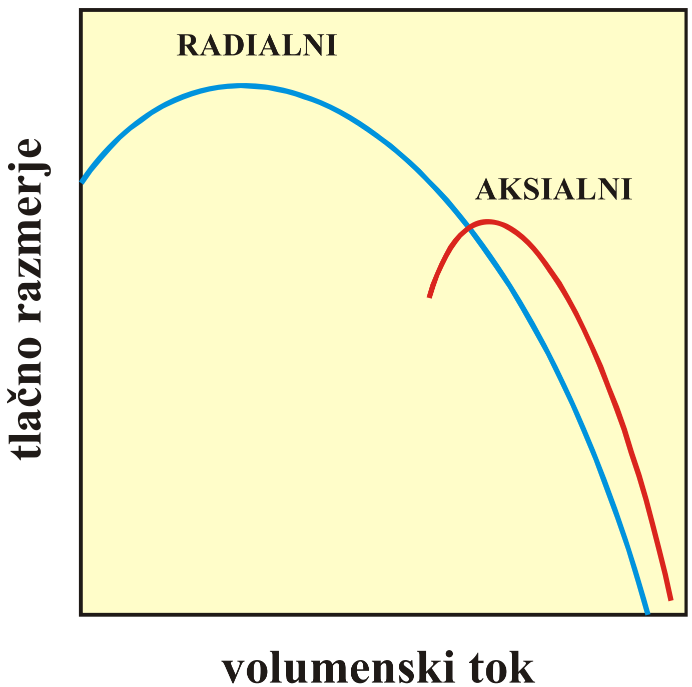


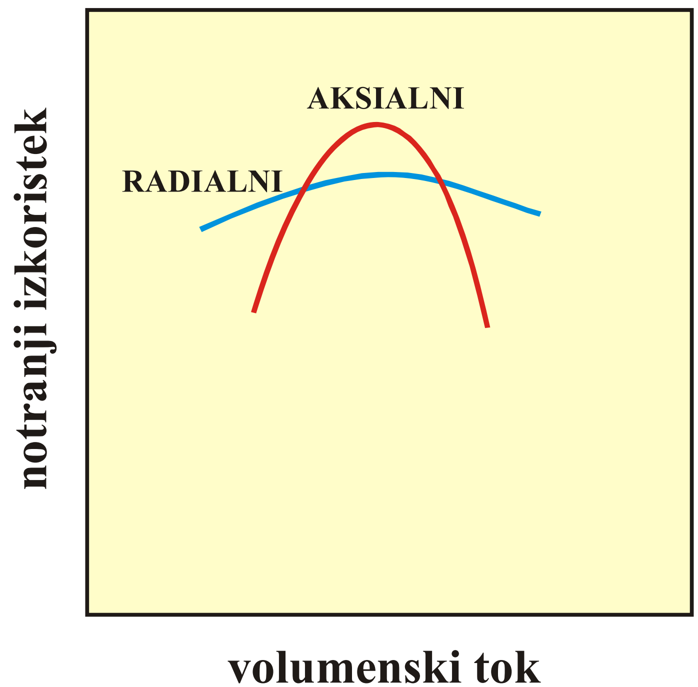


TURBOKOMPRESORJI

Večstopenjski aksialni kompresor (pri plinskem postroju)

Karakteristika in regulacija



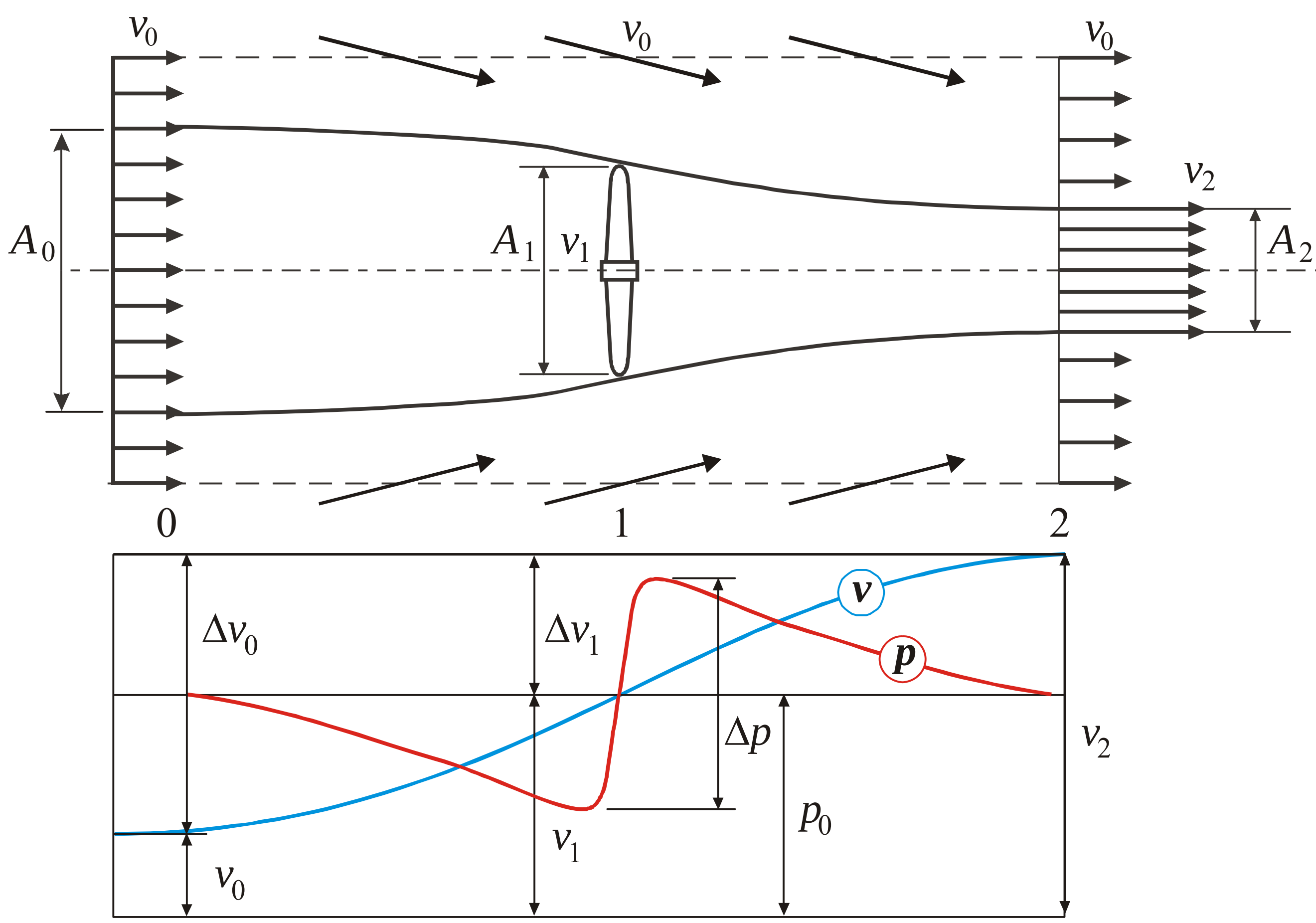


- **zaporedna namestitev stopenj: povečuje se tlačno razmerje**
- **vzporedna namestitev stopenj: povečuje se pretok**

Propeler

- **Delovni stroj za zagotavljanje aksialne potisne sile**
- **Stopnja reaktivnosti: 1 (nadtlačna stopnja)**
- **Gostota se ne spreminja:** $\rho = konst.$
- **Število lopat: 2-6**
- **Značilna vrtilna frekvenca: (300–1000) min^{-1}**
- **Omejitve pri obratovanju:**
  - **zrak: zvočna hitrost**
  - **voda: kavitacija**

potek hitrosti in tlakov



Potisna sila

Sprememba gibalne količine na mejah kontrolnega volumna

$$\Delta \dot{I}_F = \dot{I}_{F0} - \dot{I}_{F2} + \dot{I}_{\mathrm{FV}} = \dot{m} \cdot (v_0 - v_2) = \rho \cdot A_1 \cdot v_1 \cdot (v_0 - v_2)$$

Potisna sila $\Delta \dot{I}_F = -F_{\mathrm{P}}$

$$F_{\mathrm{P}} = \dot{m} \cdot (v_2 - v_0) = \rho \cdot A_1 \cdot v_1 \cdot (v_2 - v_0)$$

Teoretična moč propelerja

Določitev moči na dva načina:

$$P = F_{\mathrm{P}} \cdot v_1 = \dot{m} \cdot (v_2 - v_0) \cdot v_1 =$$

potisna sila

$$= \dot{m} \cdot \left(\frac{v_2^2}{2} - \frac{v_0^2}{2} \right)$$

sprememba energijskih tokov

Dejanska (potisna) moč propelerja in izkoristek

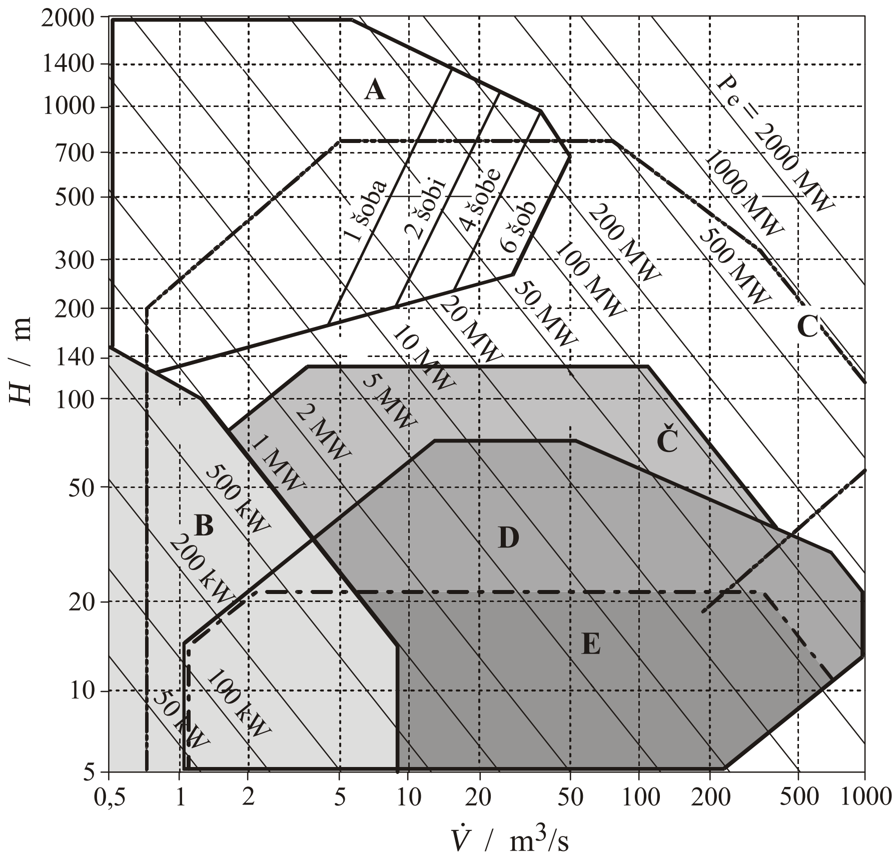
$$P_{\mathrm{e}} = F_{\mathrm{P}} \cdot v_0 = \dot{m} \cdot \left(v_2 - v_0\right) \cdot v_0$$

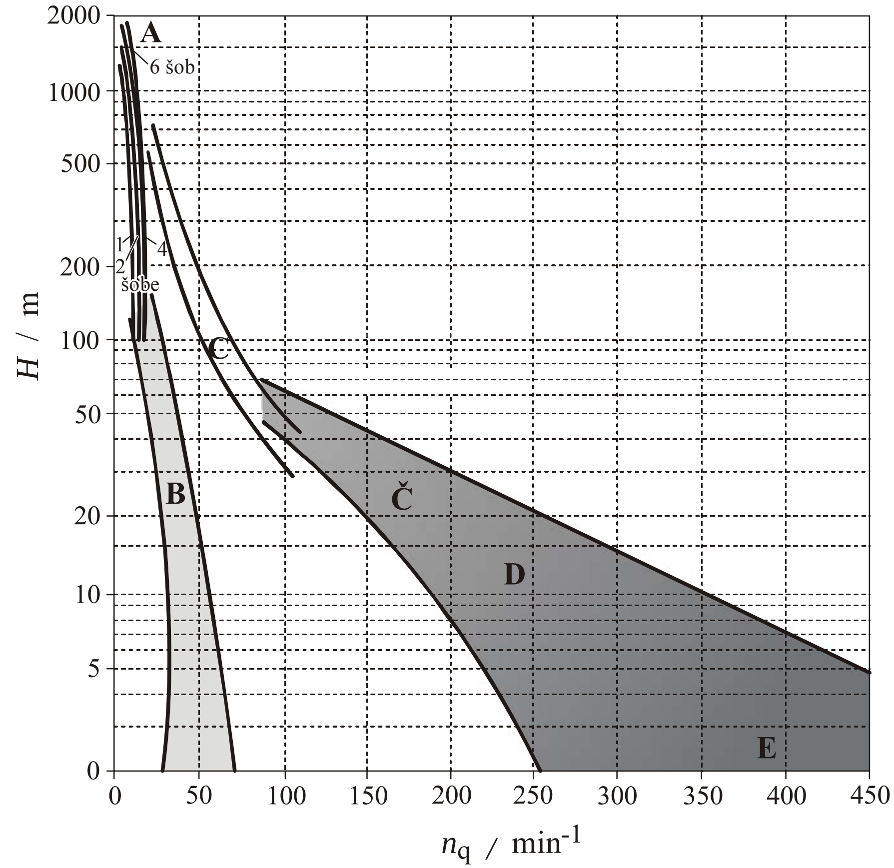
$$\eta_{\mathrm{P}} = \frac{P_{\mathrm{e}}}{P} = \frac{\dot{m} \cdot \left(v_2 - v_0\right) \cdot v_0}{\dot{m} \cdot \left(\frac{v_2^2}{2} - \frac{v_0^2}{2}\right)} = \frac{1}{1 + \frac{\Delta v_0}{2 \cdot v_0}}$$

VODNE TURBINE

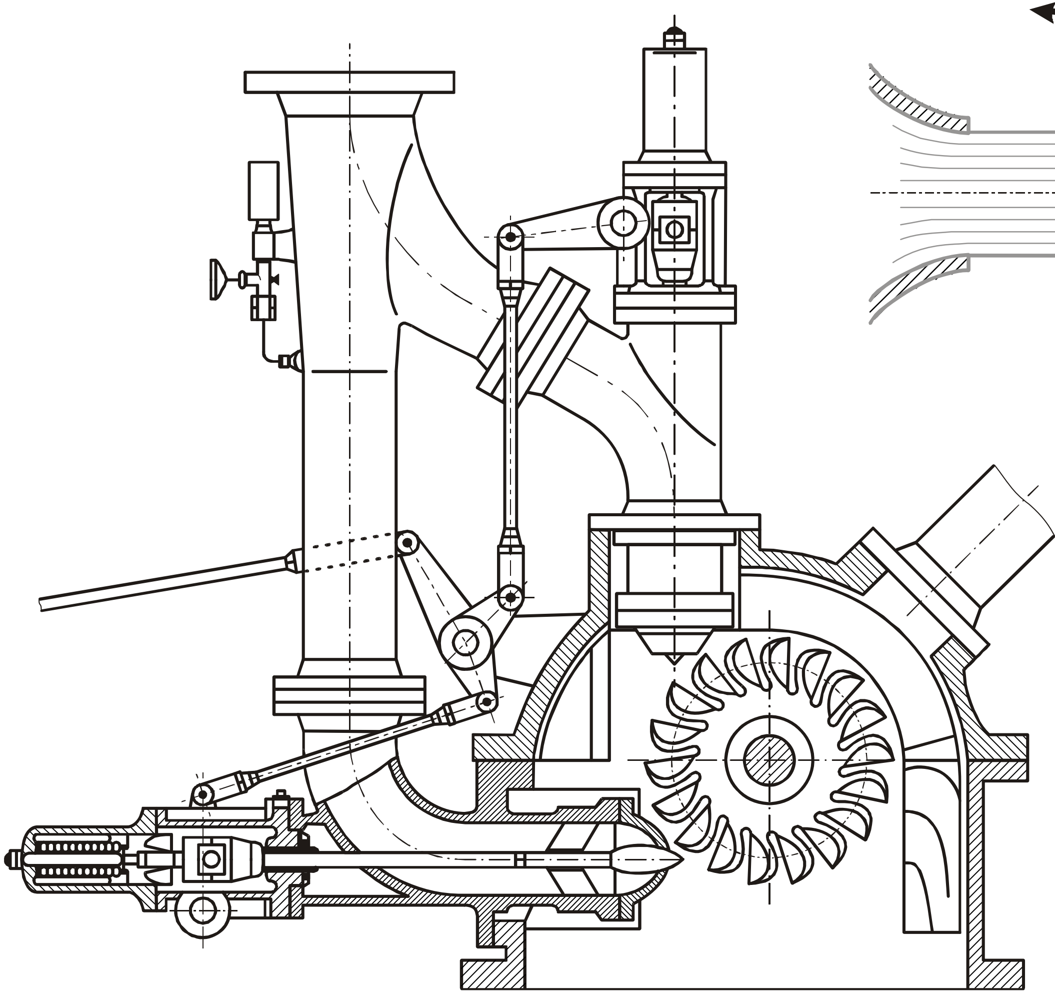
- **Pogonski stroji: potencialna energija v mehansko delo**
- **delovna snov voda (razmeroma velika gostota)**
- **izkoriščanje obnovljivih virov energije**
- **visok skupni izkoristek pretvorbe**
- **enostavna zgradba, enostopenjska konstrukcija**
- **draga gradnja**
- **dolga življenjska doba**
- **velika zanesljivost obratovanja**
- **enostavna regulacija (pretočna, spreminjanje kotov lopatic)**
- **nevarnost kavitacije**

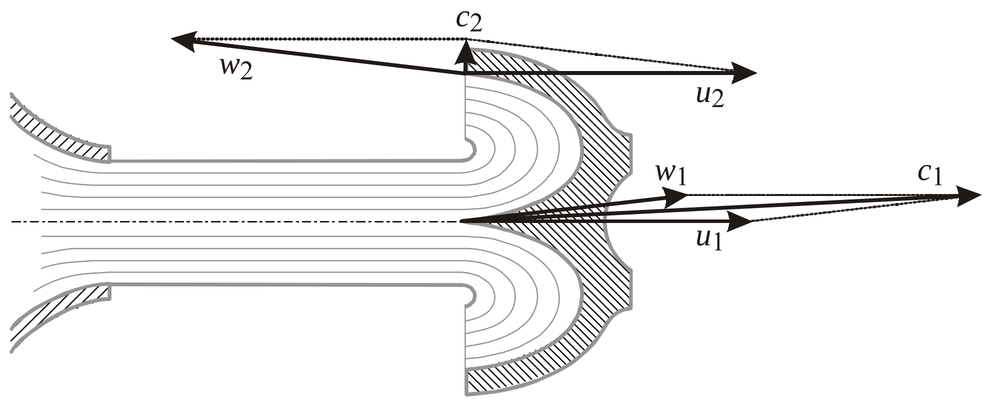
VODNE TURBINE



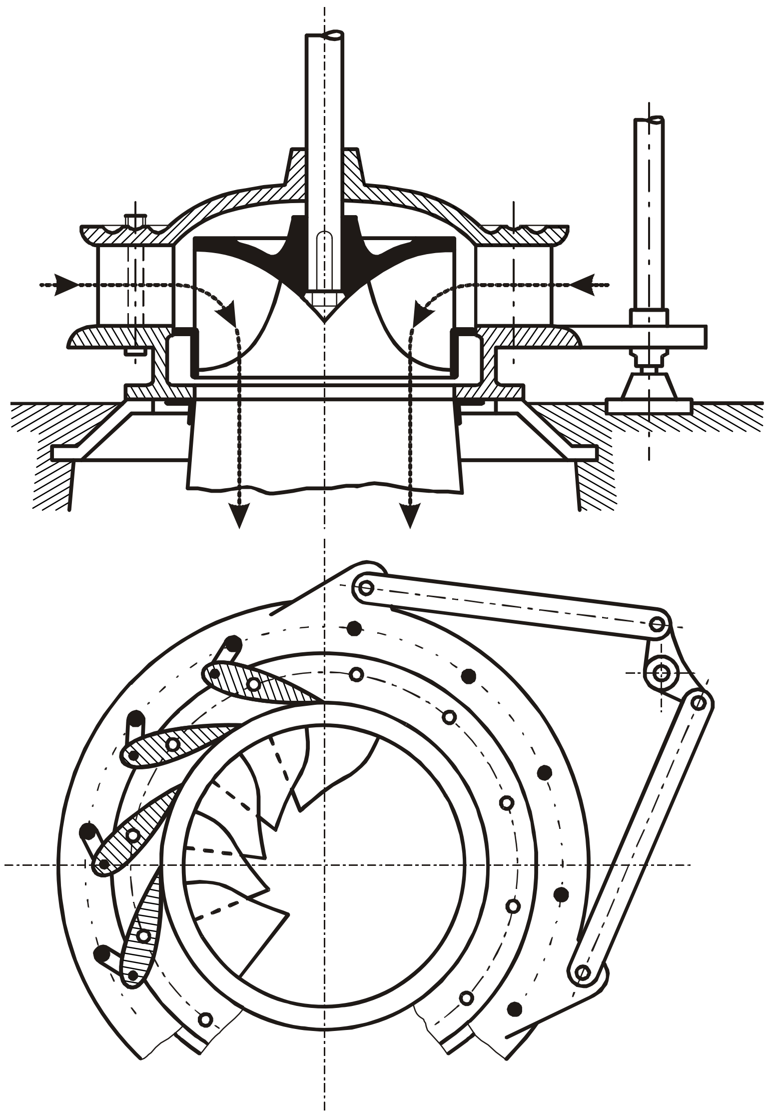


Peltonova turbina

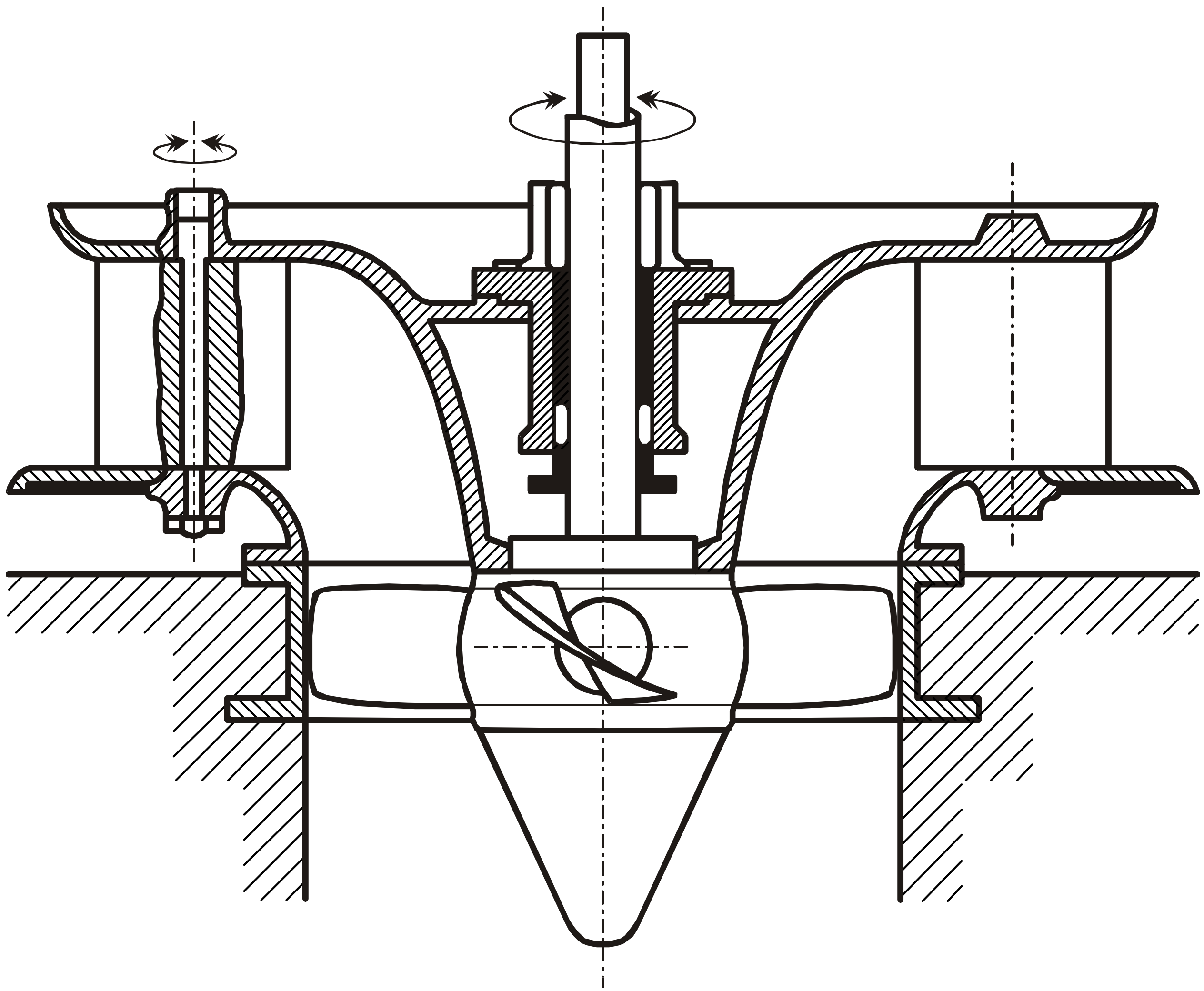




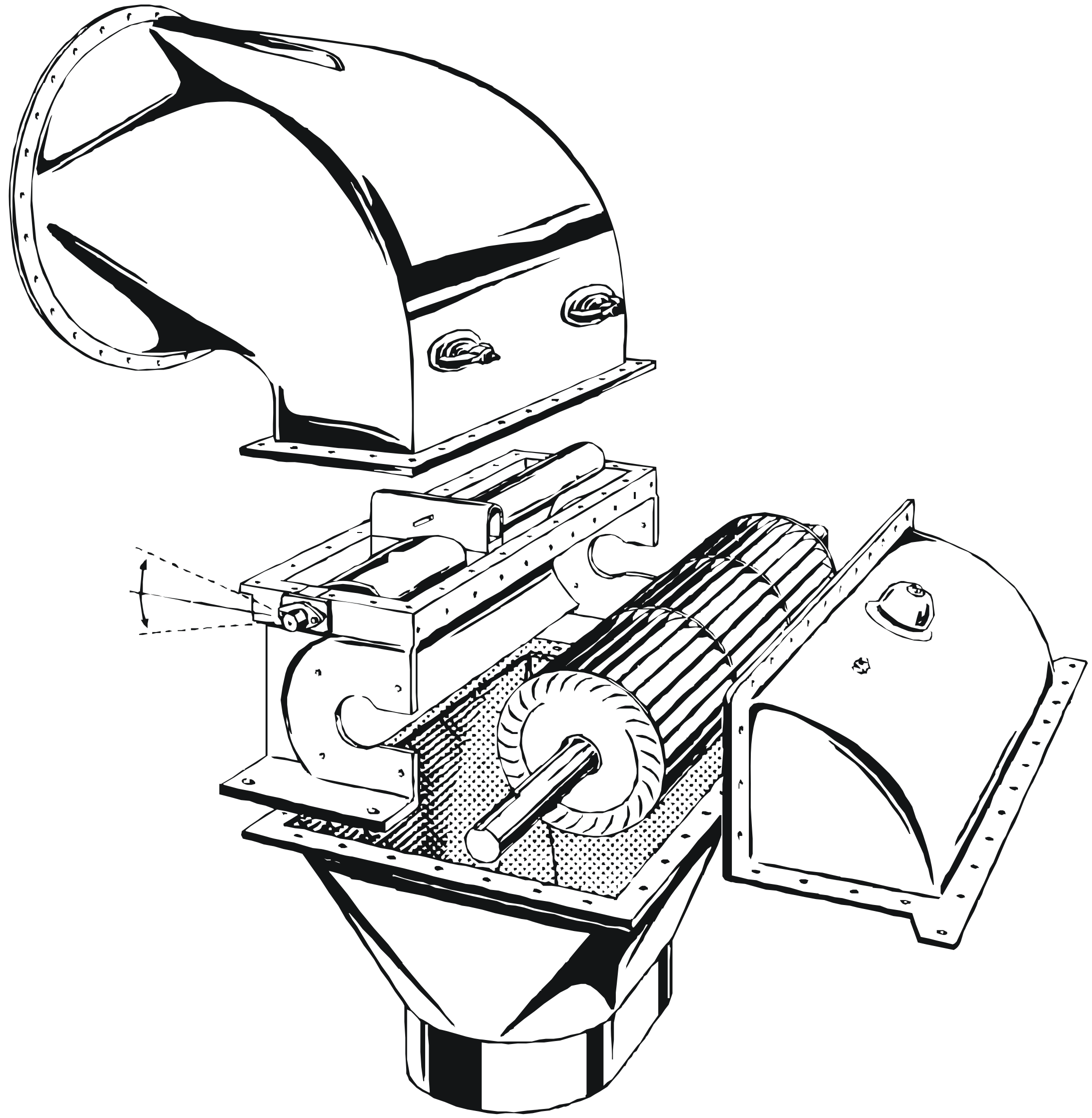
Francisova turbina



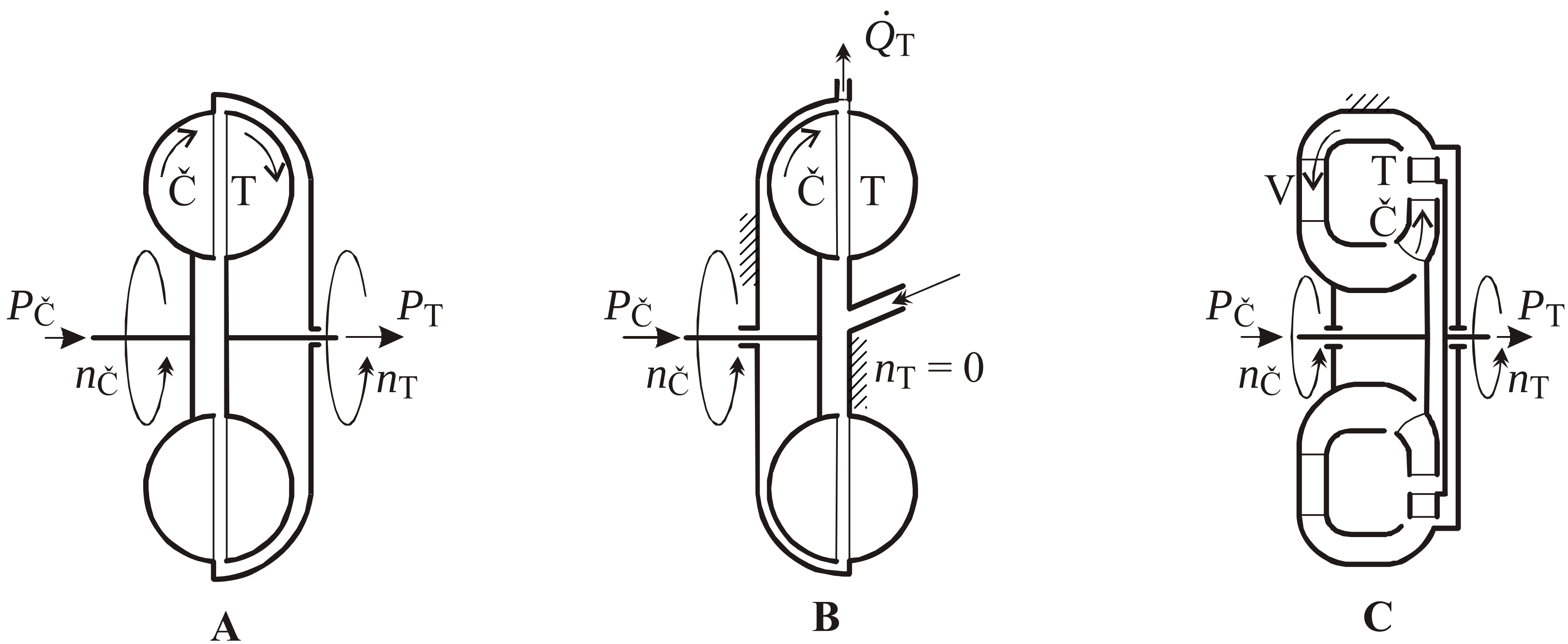
Kaplanova turbina



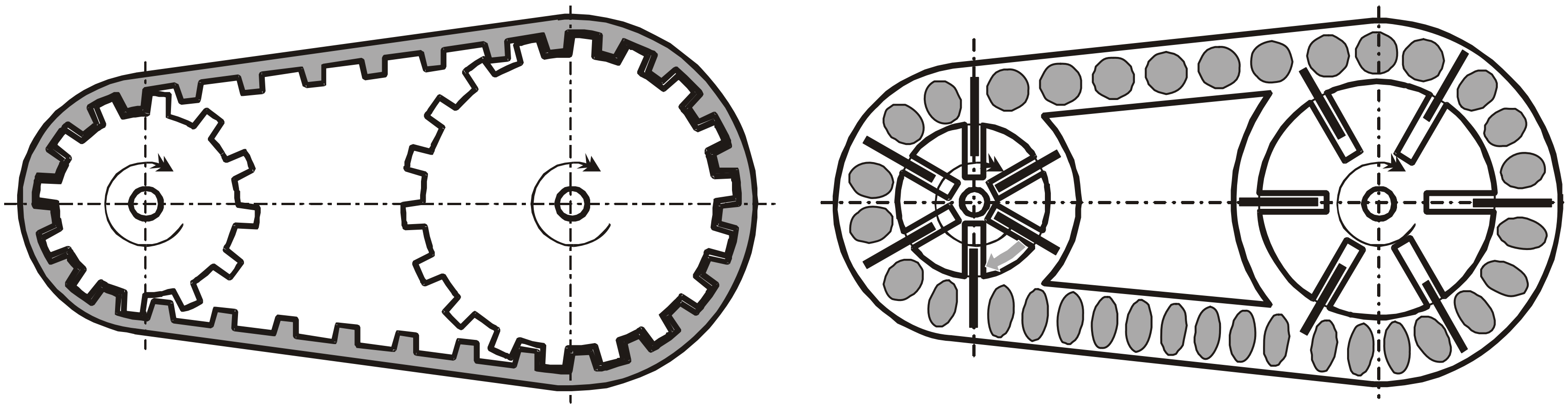
Bankijeva turbina



Hidrodinamični prenosniki moči



Hidrodinamični prenosniki moči



Hidrodinamični prenosniki moči