

# ***Turbinas Hidráulicas***

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## ***Turbomáquinas Hidráulicas***

***CT-3411***

Prof. Jesus De Andrade

Prof. Miguel Asuaje



# Turbina Kaplan

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**Descripción,  
Clasificación, Dimensionamiento y  
Curvas Características**



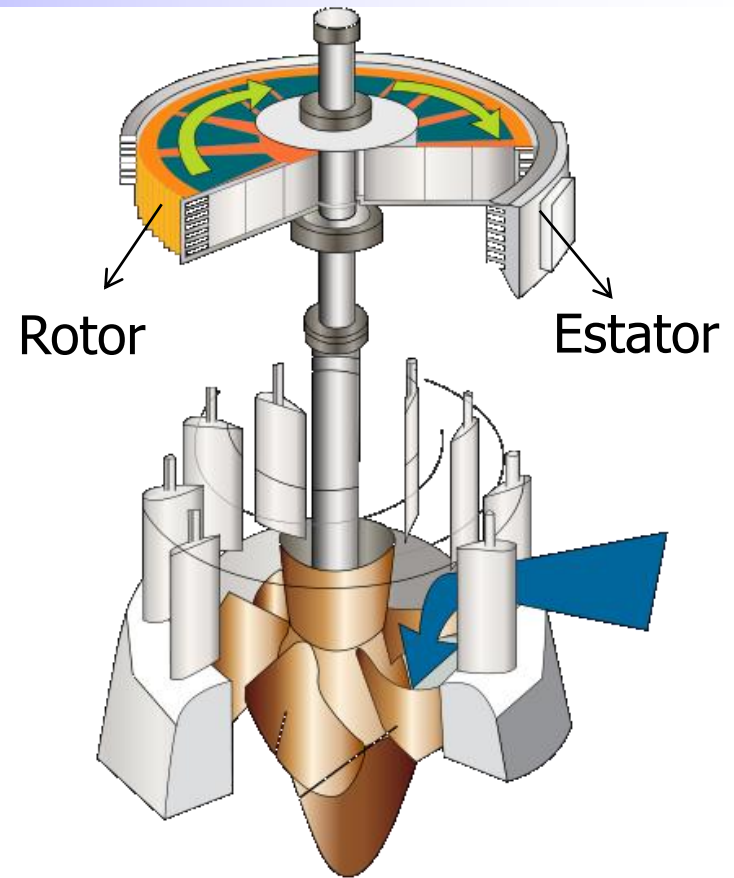
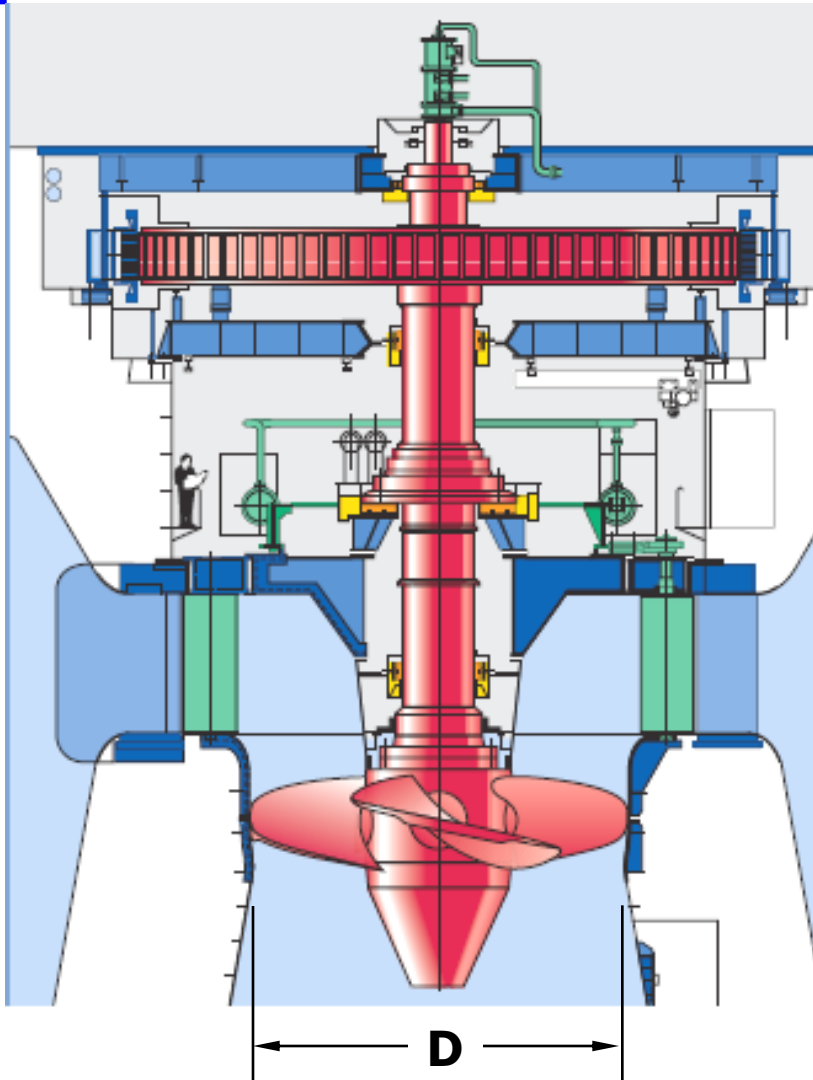
# Turbina Kaplan

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## Características Generales

- Turbina de reacción.
- Flujo axial  $U = U_1 = U_2$ ,  $V_R = 0$
- Saltos netos entre 4 y 80 m (rango competitivo hasta 20 m).
- Rango de  $n_s$ : 350 a 600
- $\eta \geq 90\%$
- $P_{\text{máx.}} = 180$  MW. (Central Caruachi) Venezuela.
- Peligro de cavitación
- Problemas de transporte por su gran tamaño.
- Máxima capacidad de regulación de carga Doble regulación alabes del aparato distribuidor y rodete ajustables.

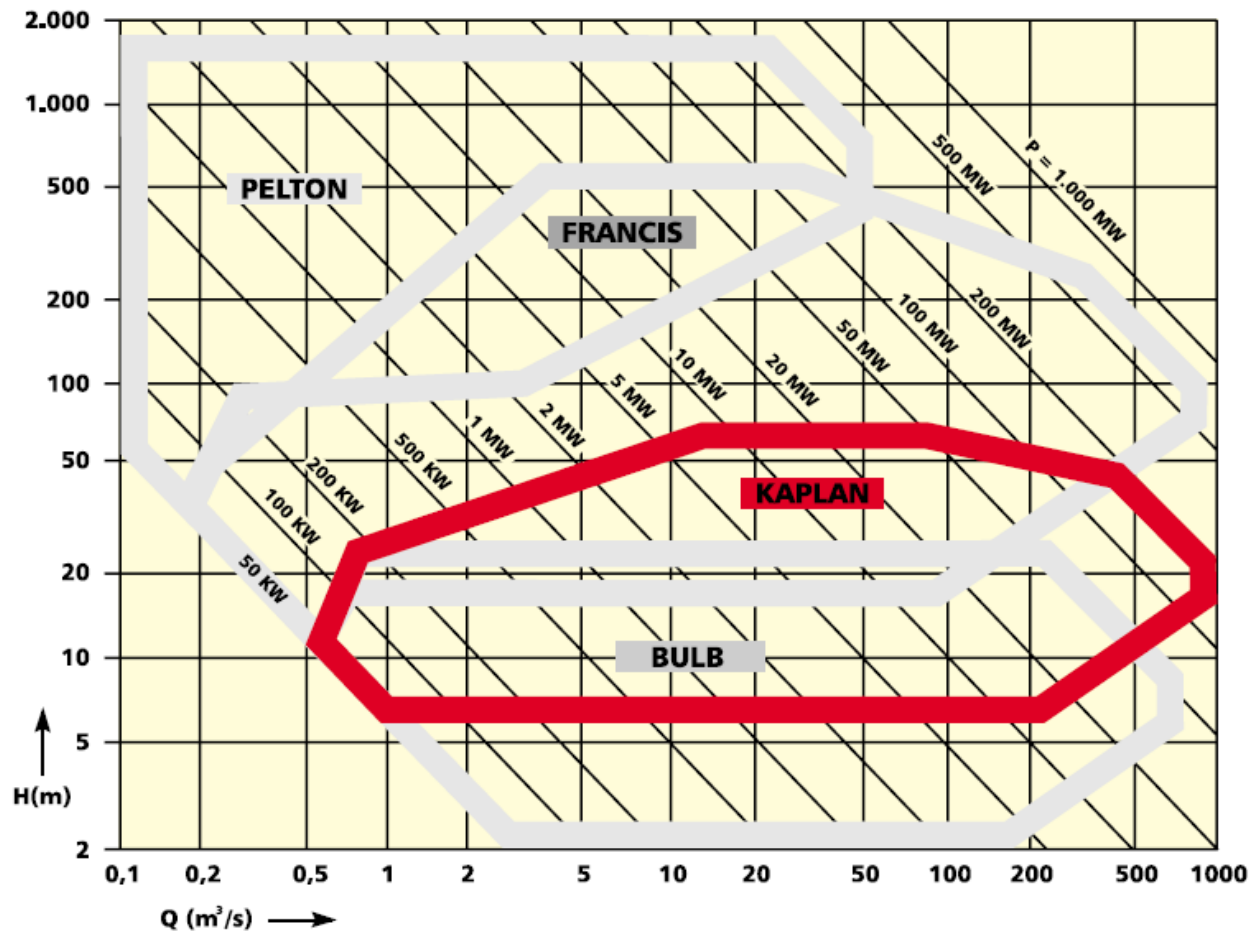
# Turbina Kaplan



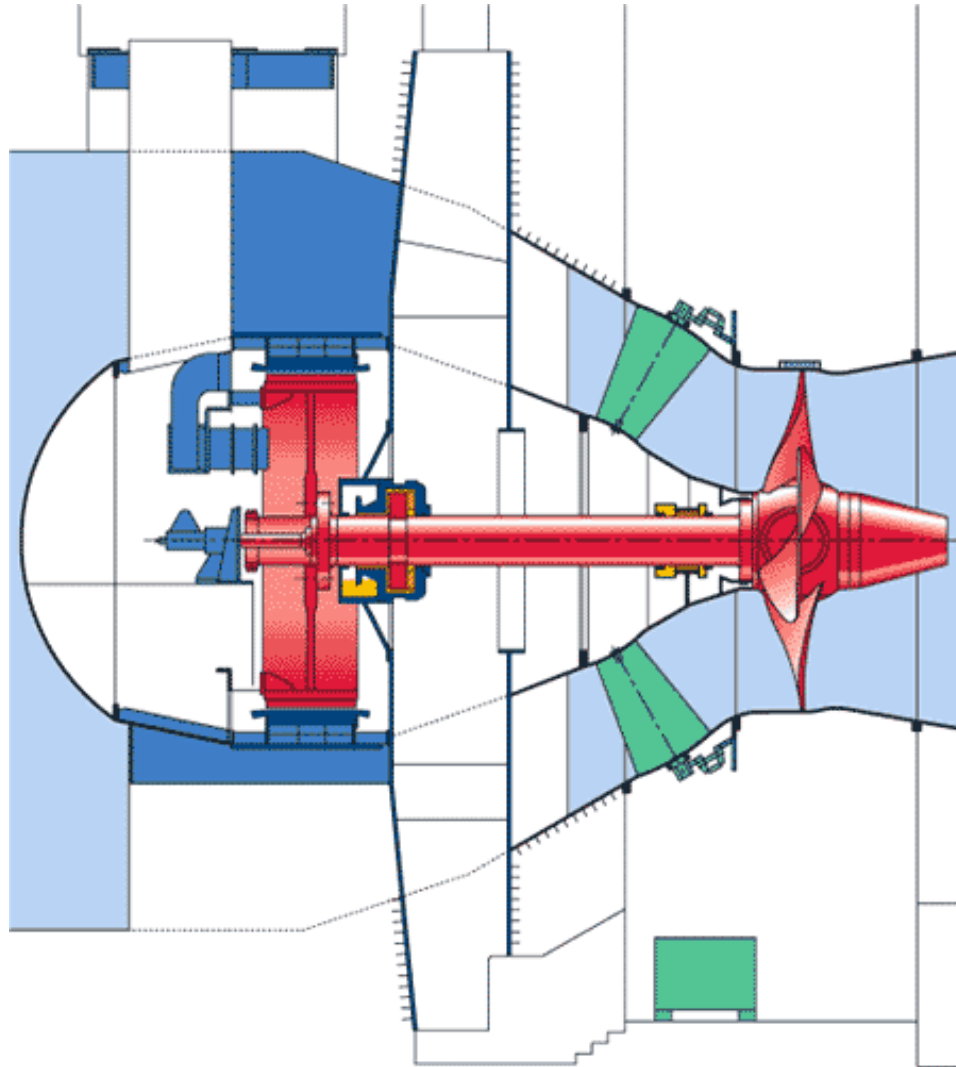
*Turbina Kaplan de diámetro  
 $D = 9,5 \text{ m}$  Central Yacretá,  
Argentina*

# Turbina Kaplan

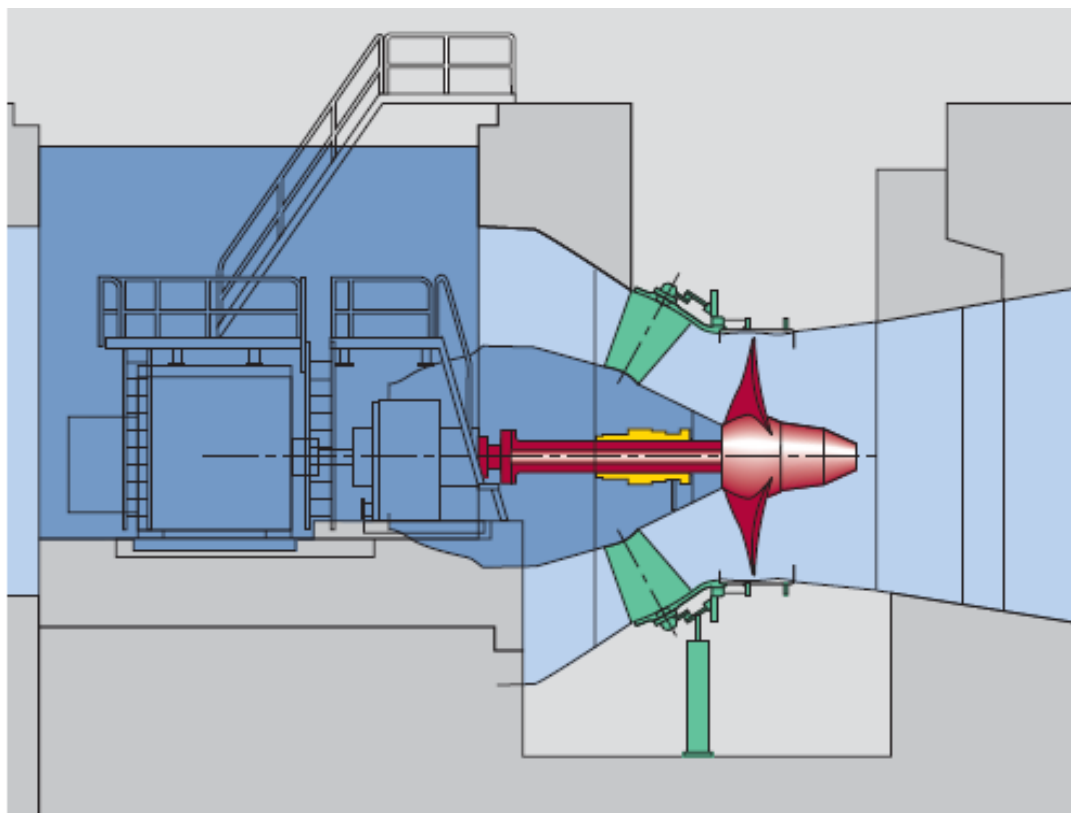
## Campo de Aplicación



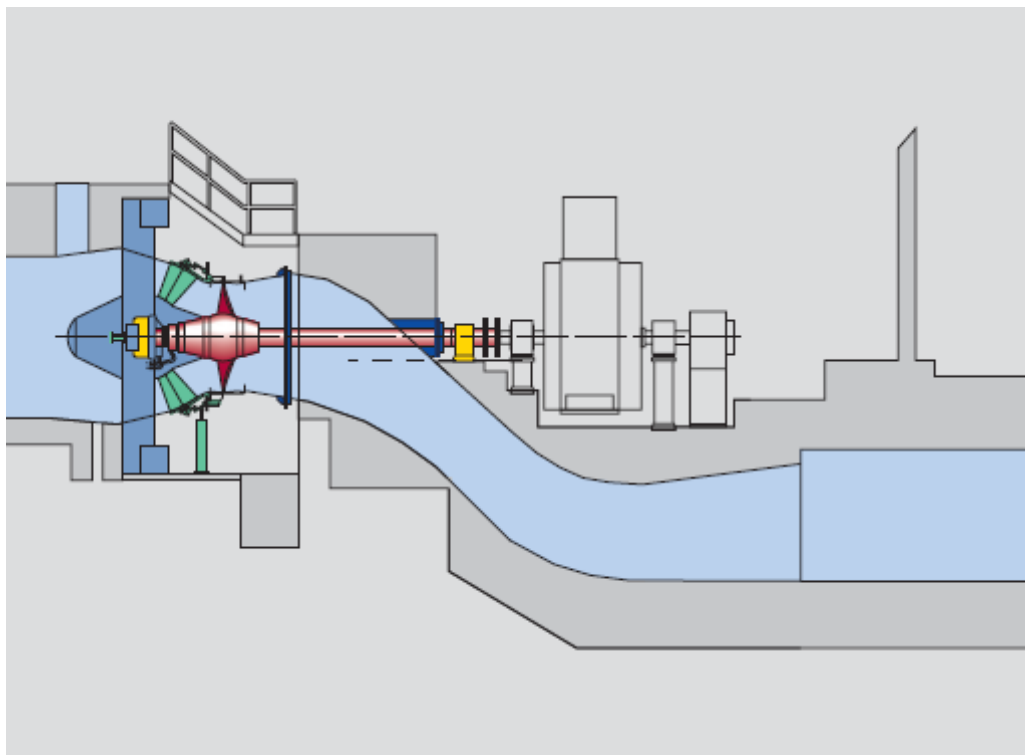
# Turbina Bulbo



# TK de pozo



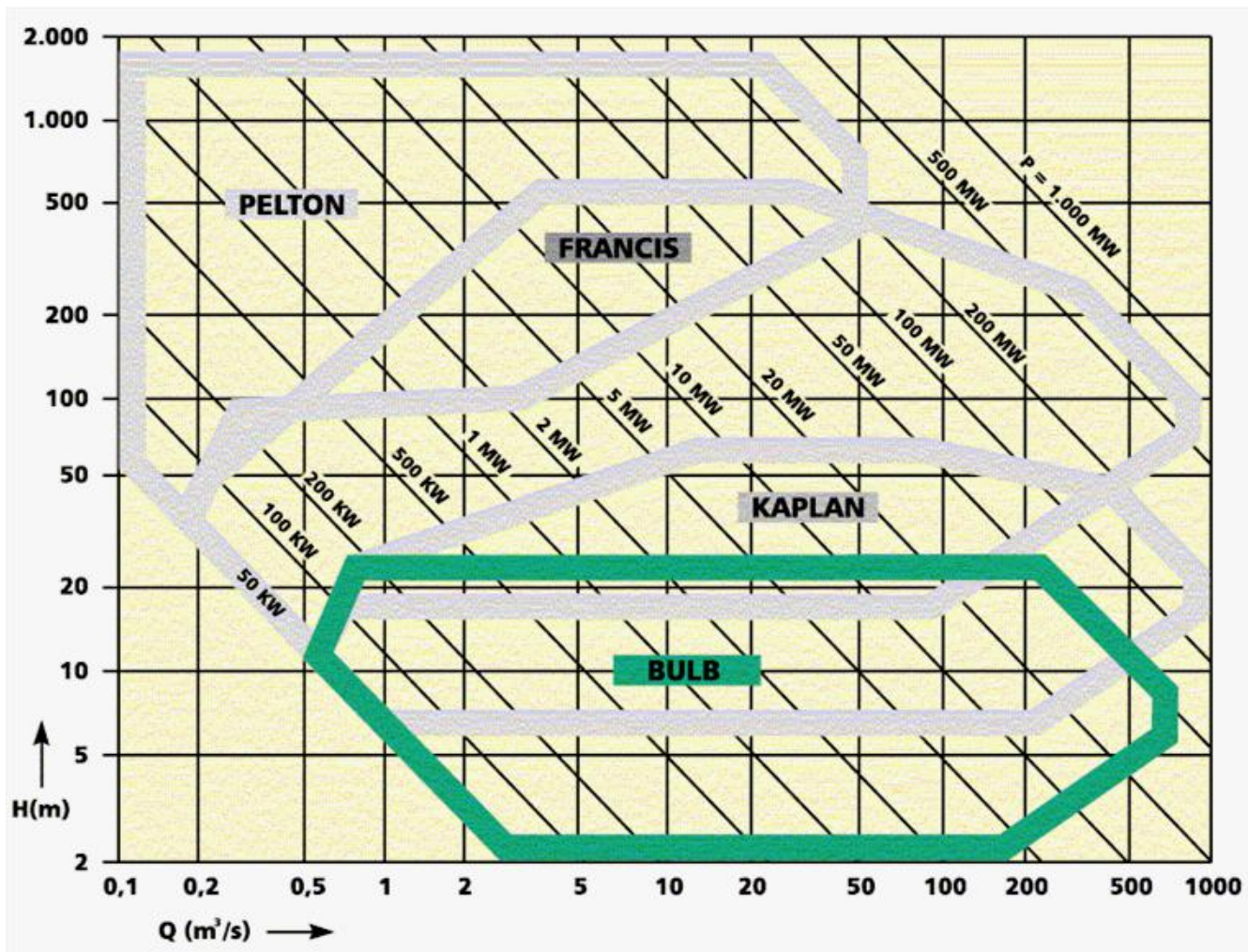
# TK tipo S





# Turbina Bulbo

## Campo de Aplicación

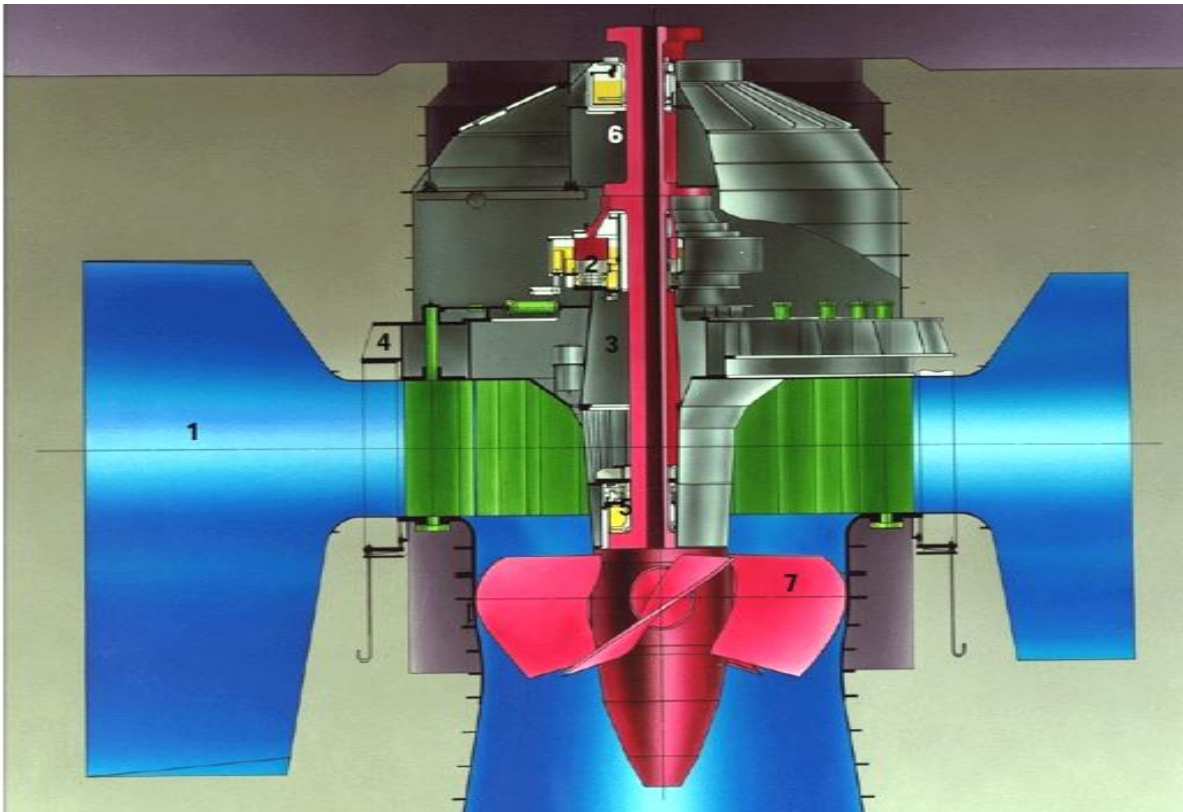




# Descripción TK

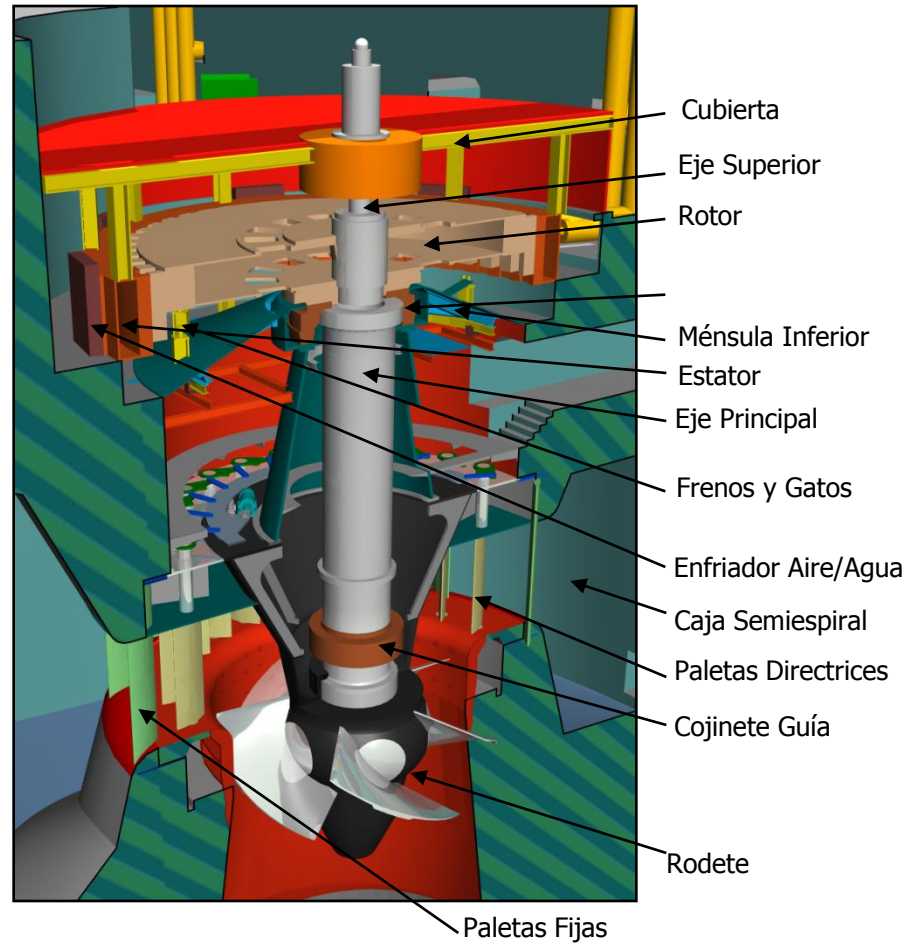
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# Turbina Kaplan

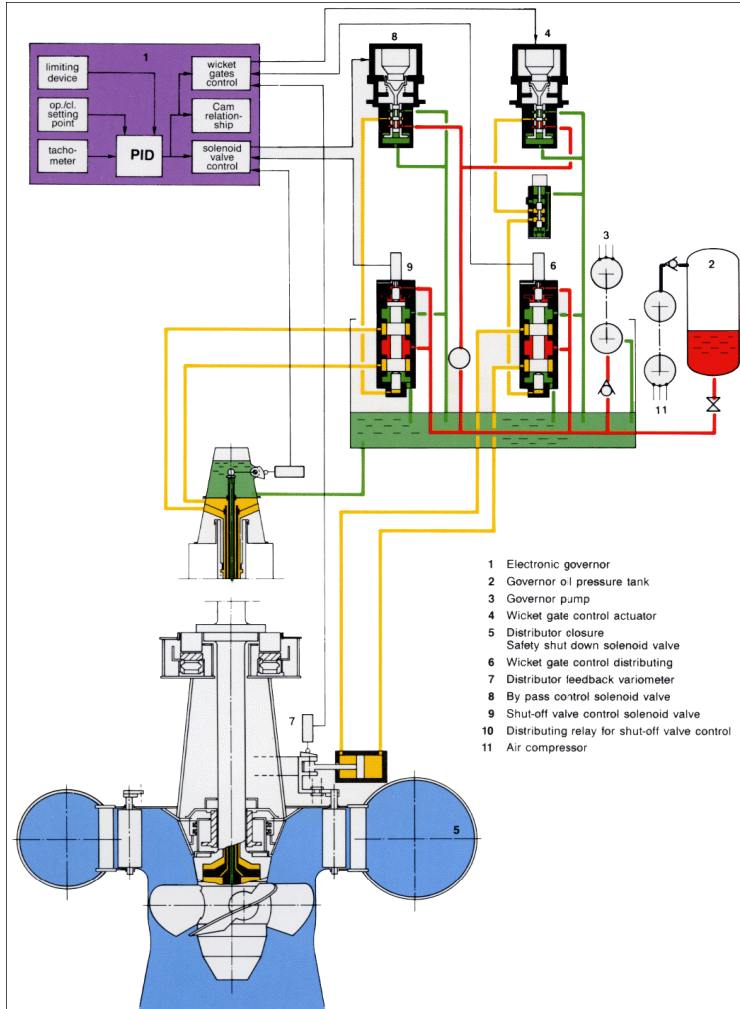
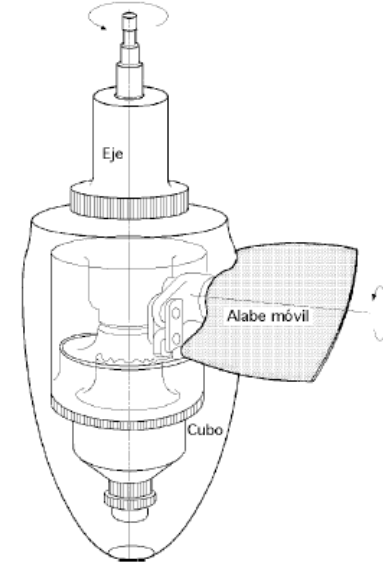


1. Concrete front spiral casing
2. Membrane thrust bearing
3. Thrust bearing support head cover
4. Embedded head cover
5. Rotating vat bearing
6. Bearing guide with supporting cross-head of the shell type
7. Blade

# Turbina Kaplan



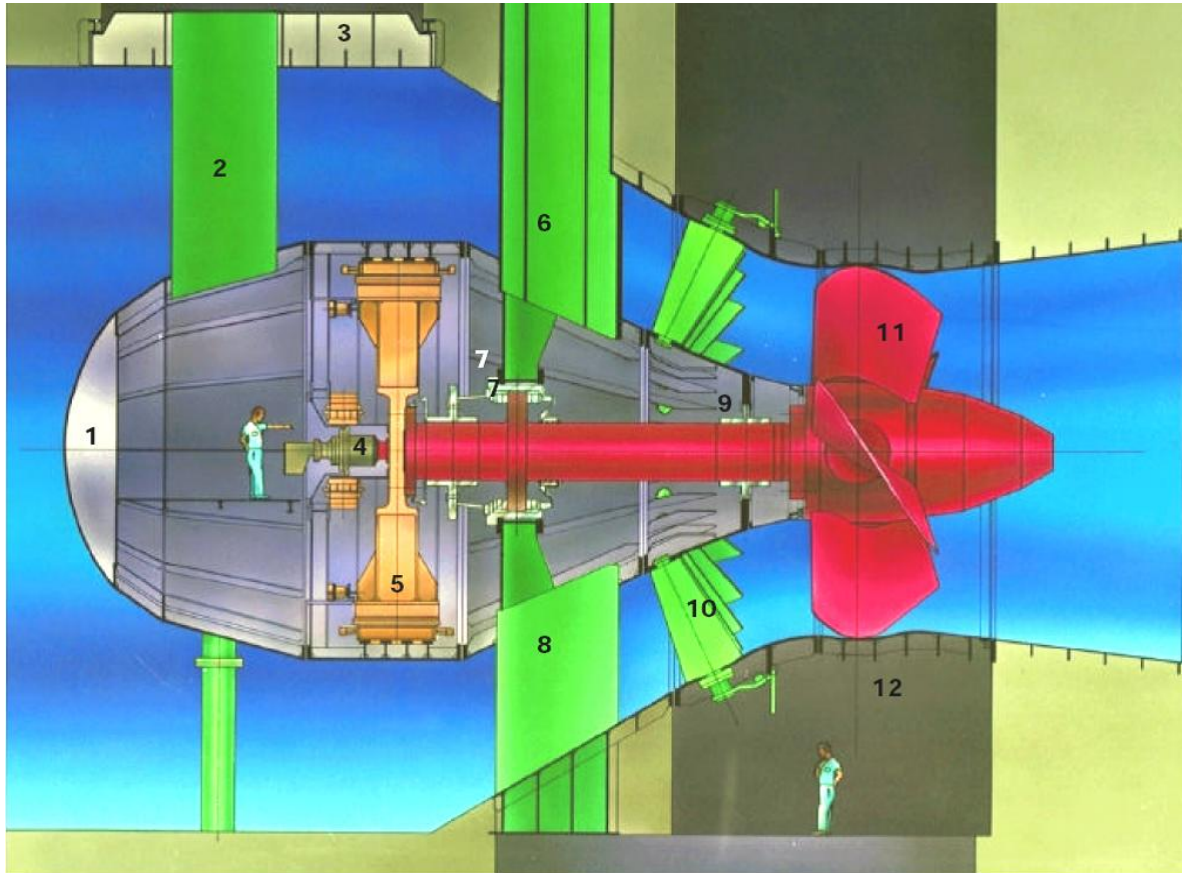
# TK Doble Regulación



Regulación simultanea de la posición de los alabes del aparato distribuidor y del rodete



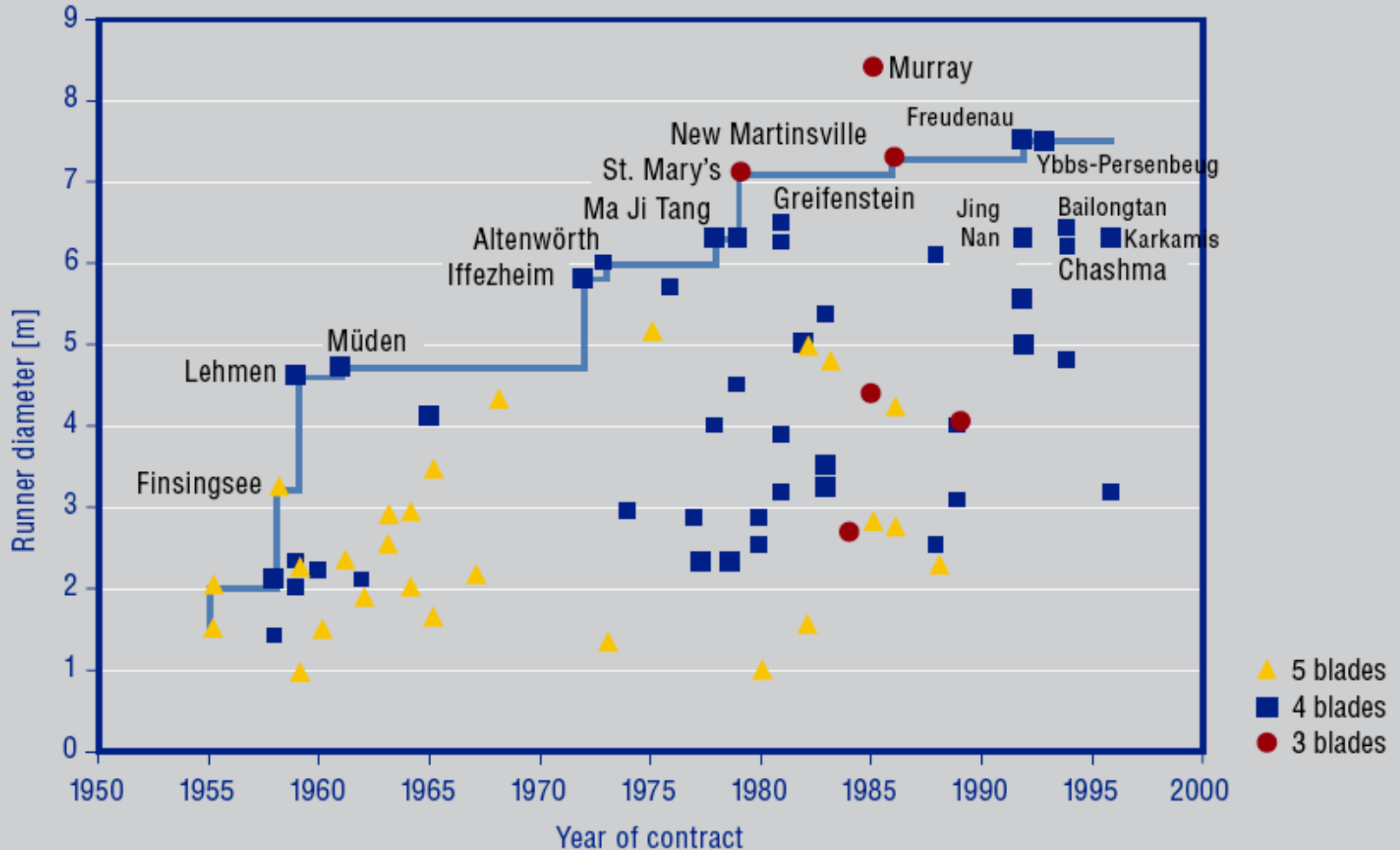
# Turbina Bulbo



1. Bulb nose
2. Access arm to the upstream compartment
3. Removable cover for generator dismantling
4. Oil distribution head
5. Generator
6. Upper stay vane for access to downstream compartment
7. Upstream thrust and counter thrust bearing
8. Lower stay vane
9. Downstream bearing
10. Adjustable distributor
11. Blade
12. Turbine pit

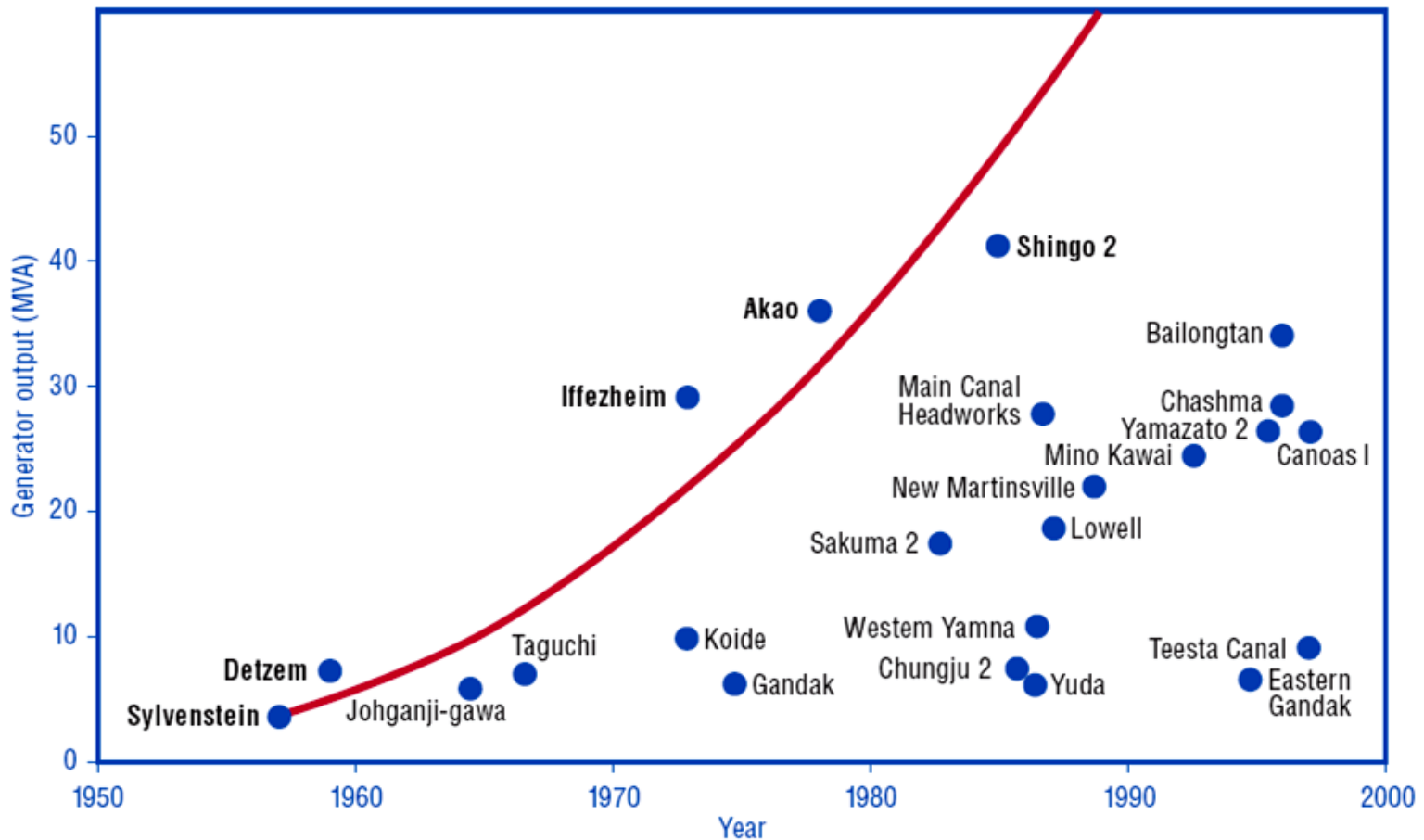
# Turbina Bulbo

Trend of runner diameter



# Turbina Bulbo

## Trend of bulb generator output

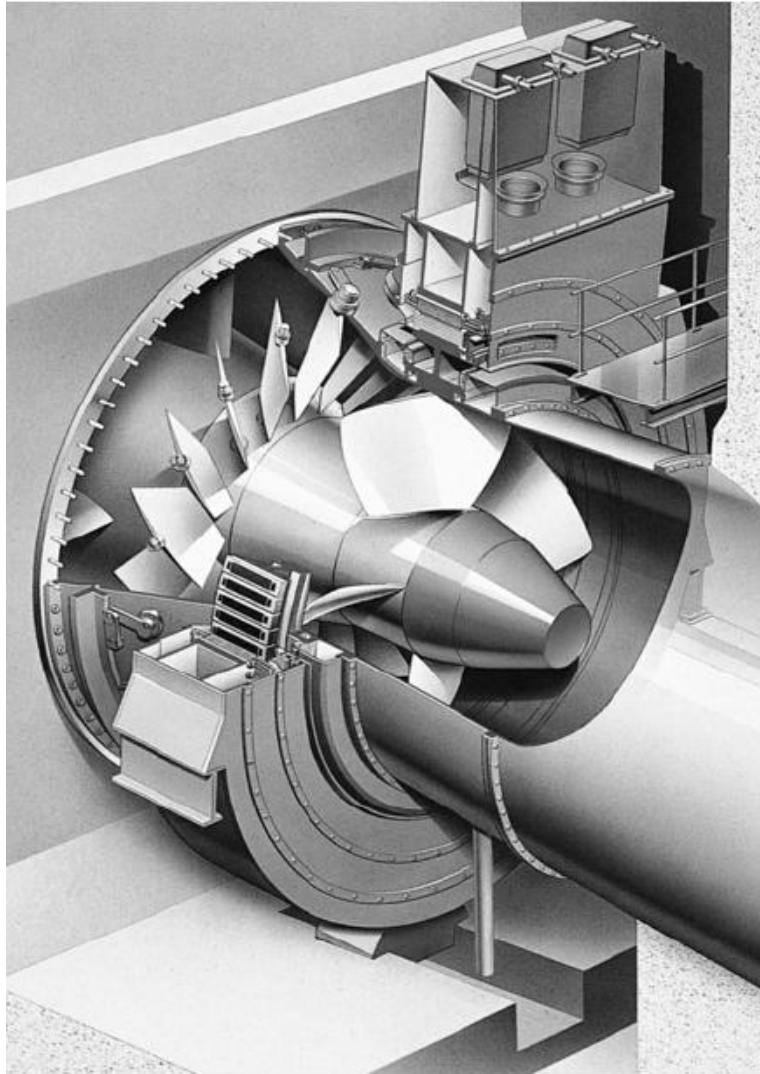




# Turbina Straflo

**Straflo**  $\equiv$  **Straight Flow**

(Turbina Axial concéntrica)



# Rodetes Turbina Kaplan

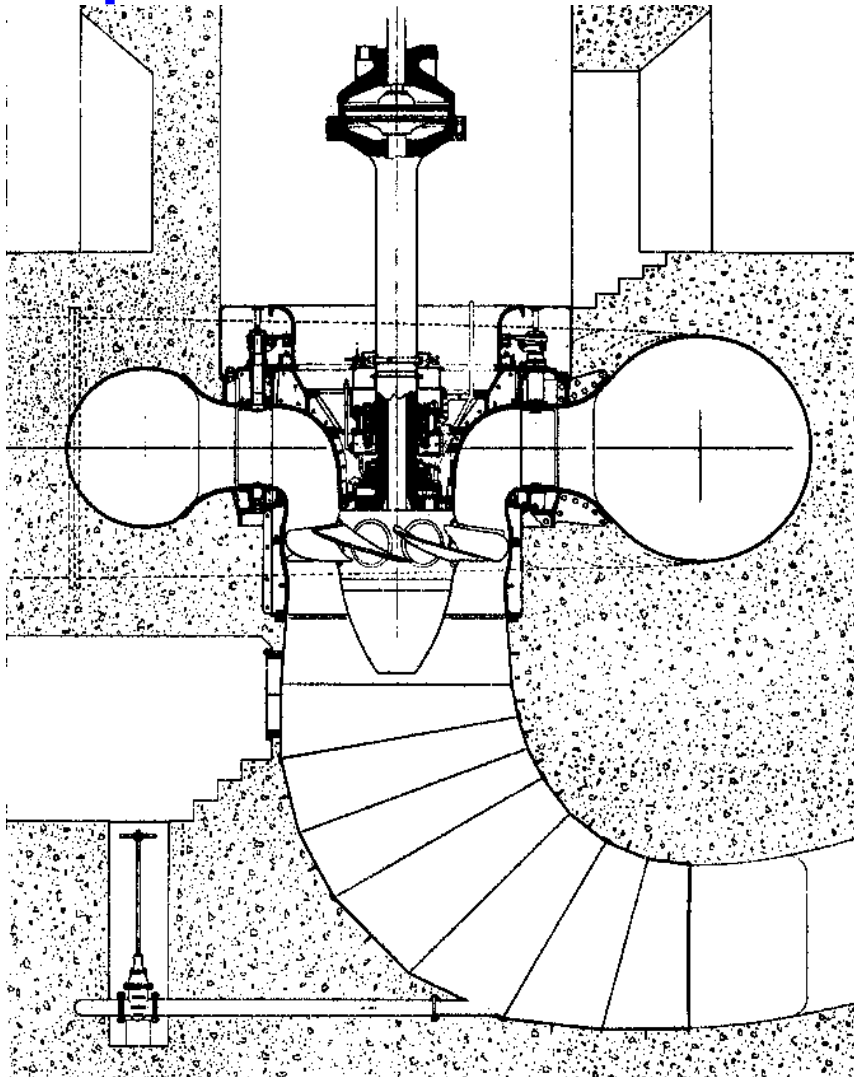


# Caja espiral Turbina Kaplan



Diámetro tubería admisión  $\phi$  6,8 m. Diámetro externo máximo igual a 20 m

# Turbina Kaplan



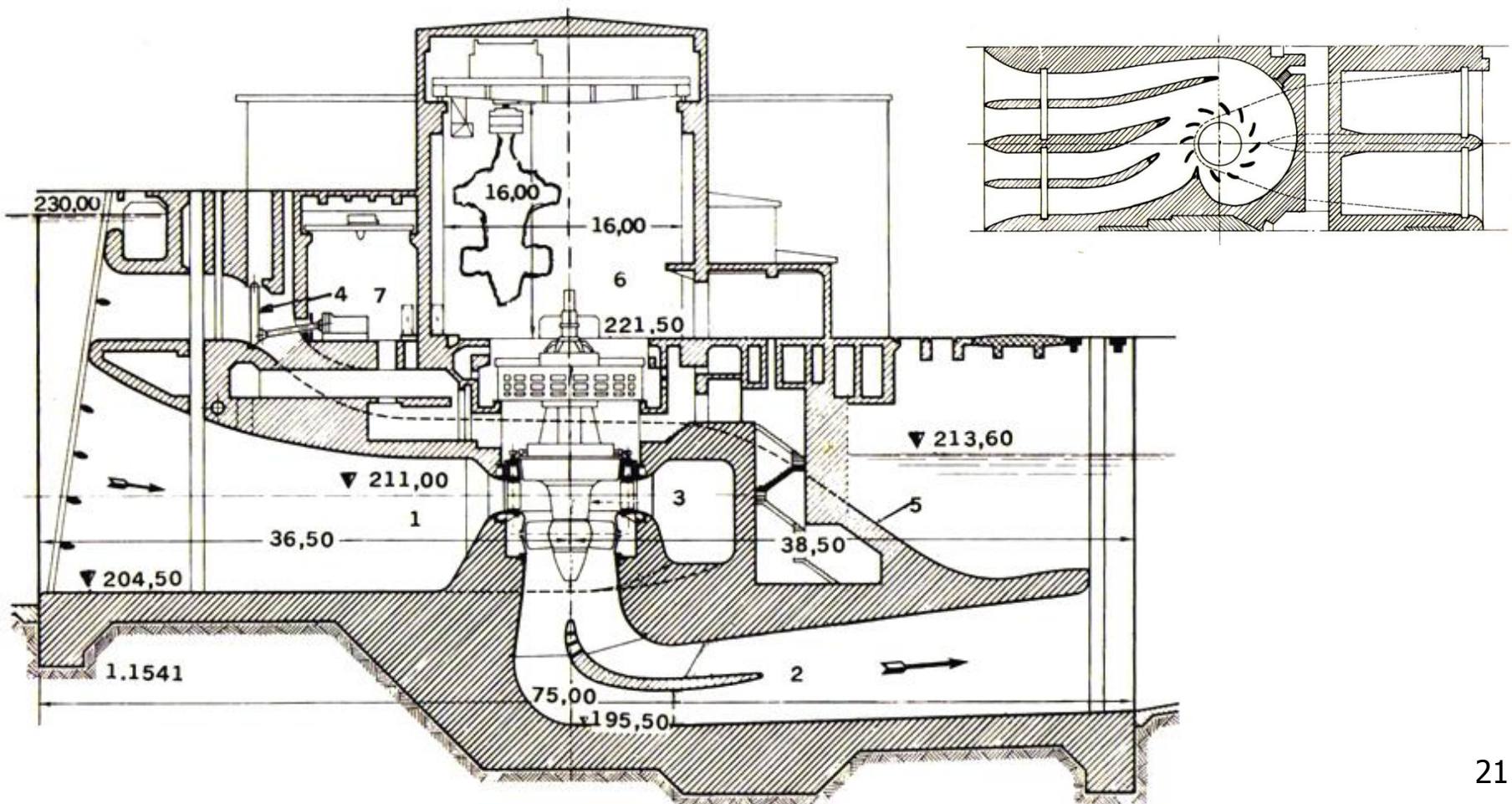
## *Central Hidroeléctrica El Oviachic (México)*

$H_n$	=	47,7	35,5 m
$Q$	=	26	30 m <sup>3</sup> /s
$P$	=	11050	9480 kW
$n$	=	300 rpm	



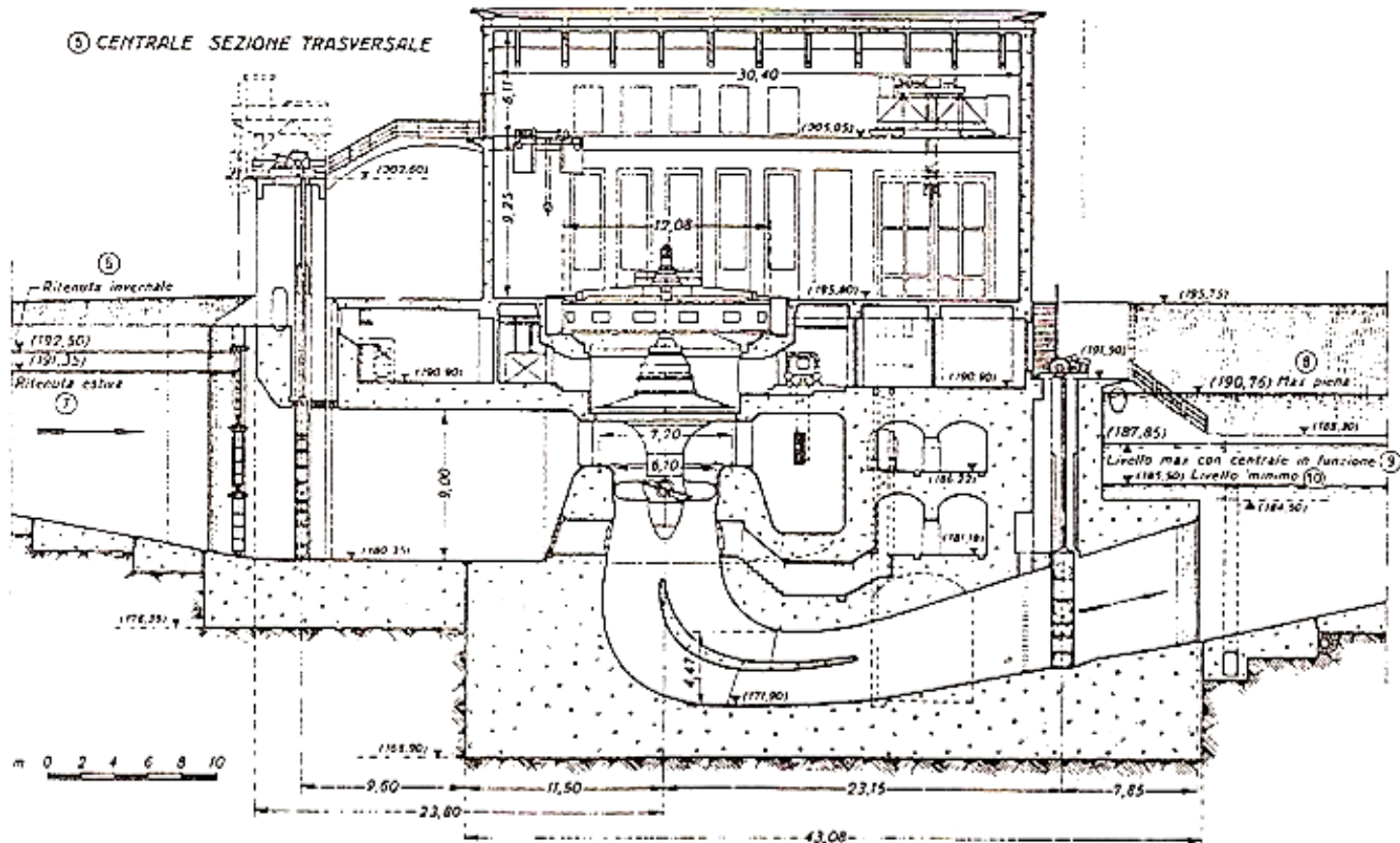
# Turbina Kaplan

## Central Hidroeléctrica Ottmarsheim

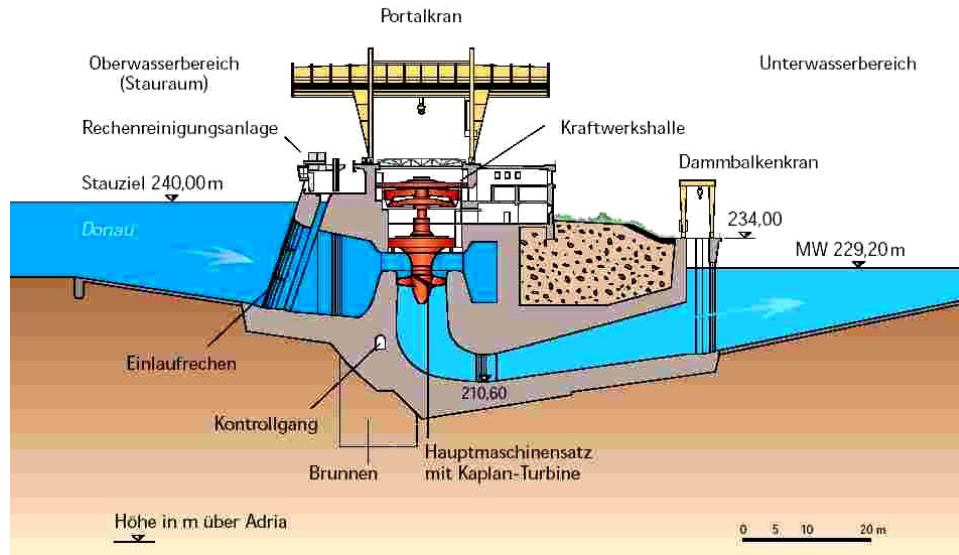


# Turbina Kaplan

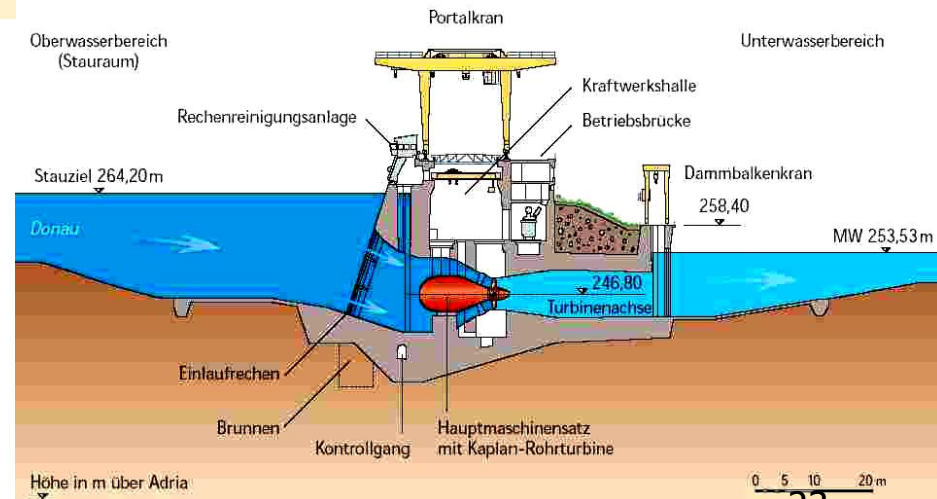
## Central Hidroeléctrica de La Torre (Italia)



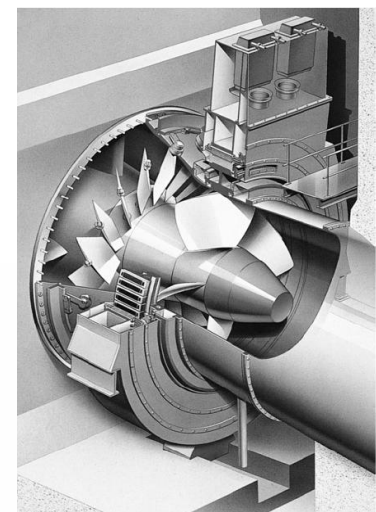
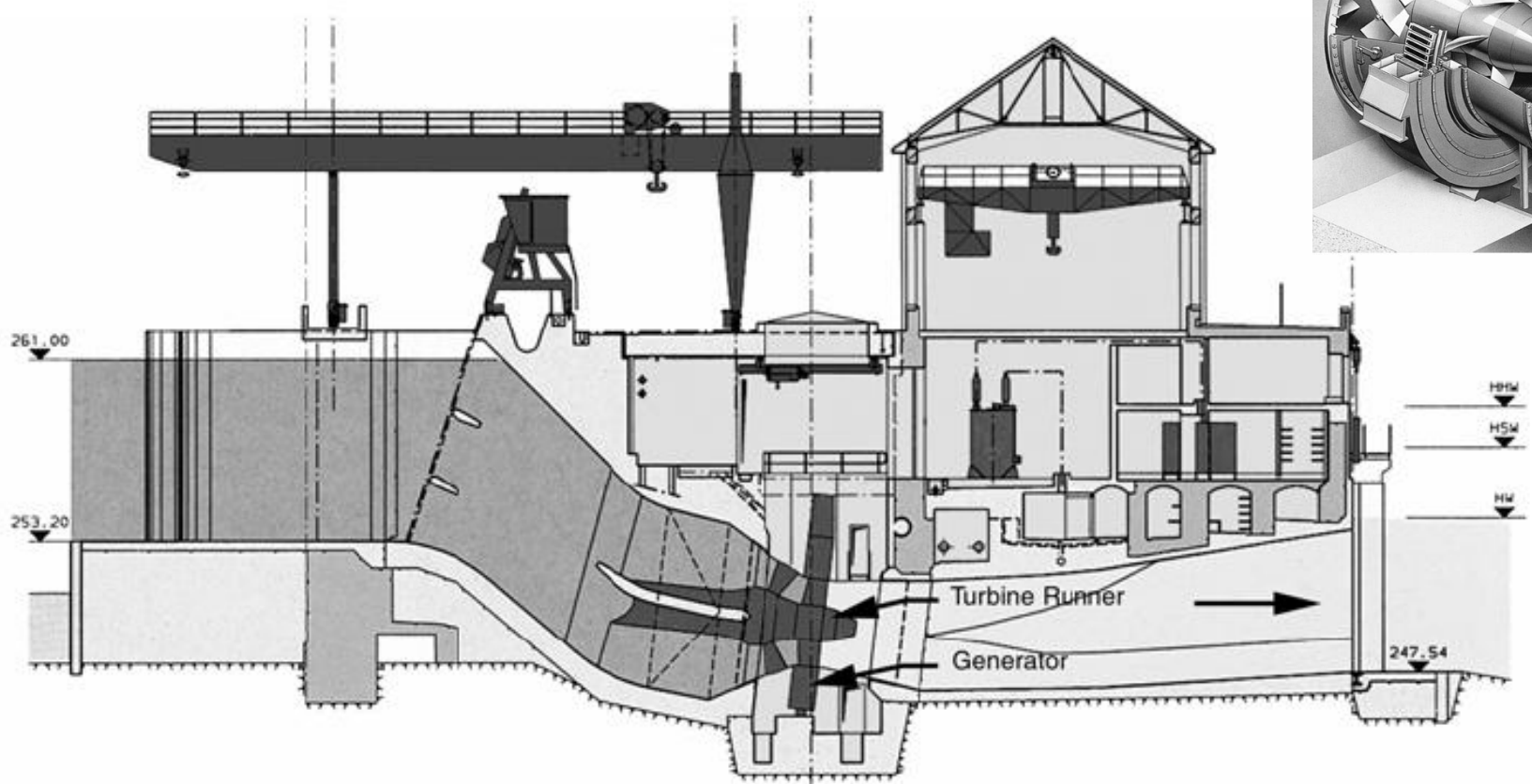
# Turbina Kaplan



## Comparación Turbina Kaplan vs. Turbina Bulbo



# Turbina Straflo







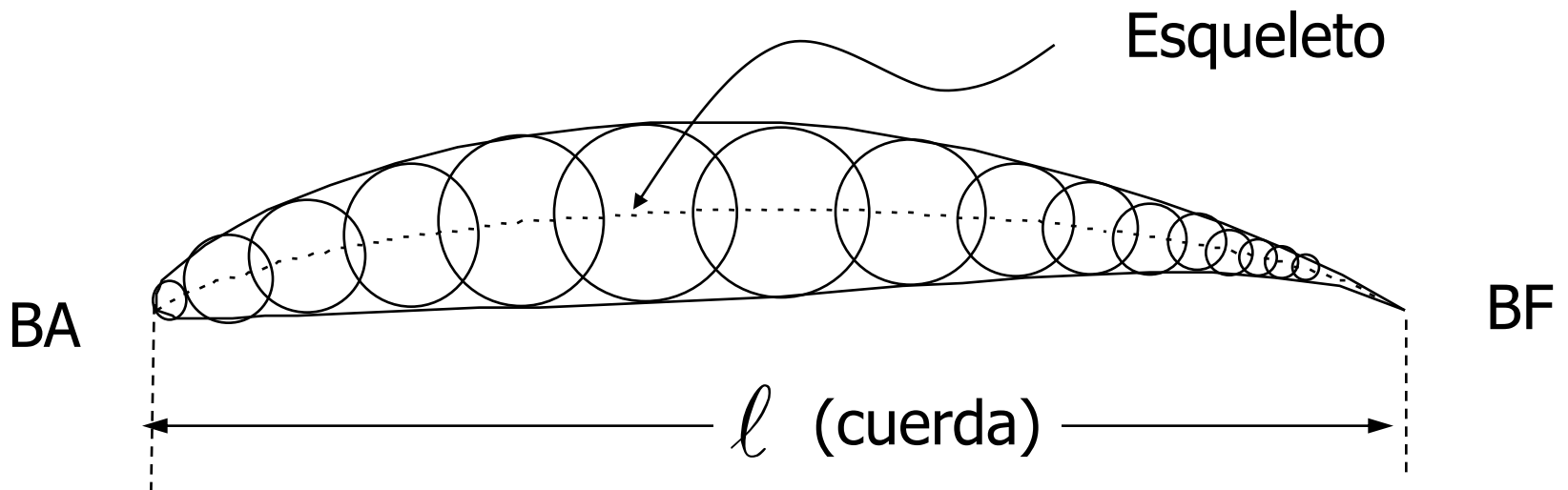
# ***Perfil Portante***

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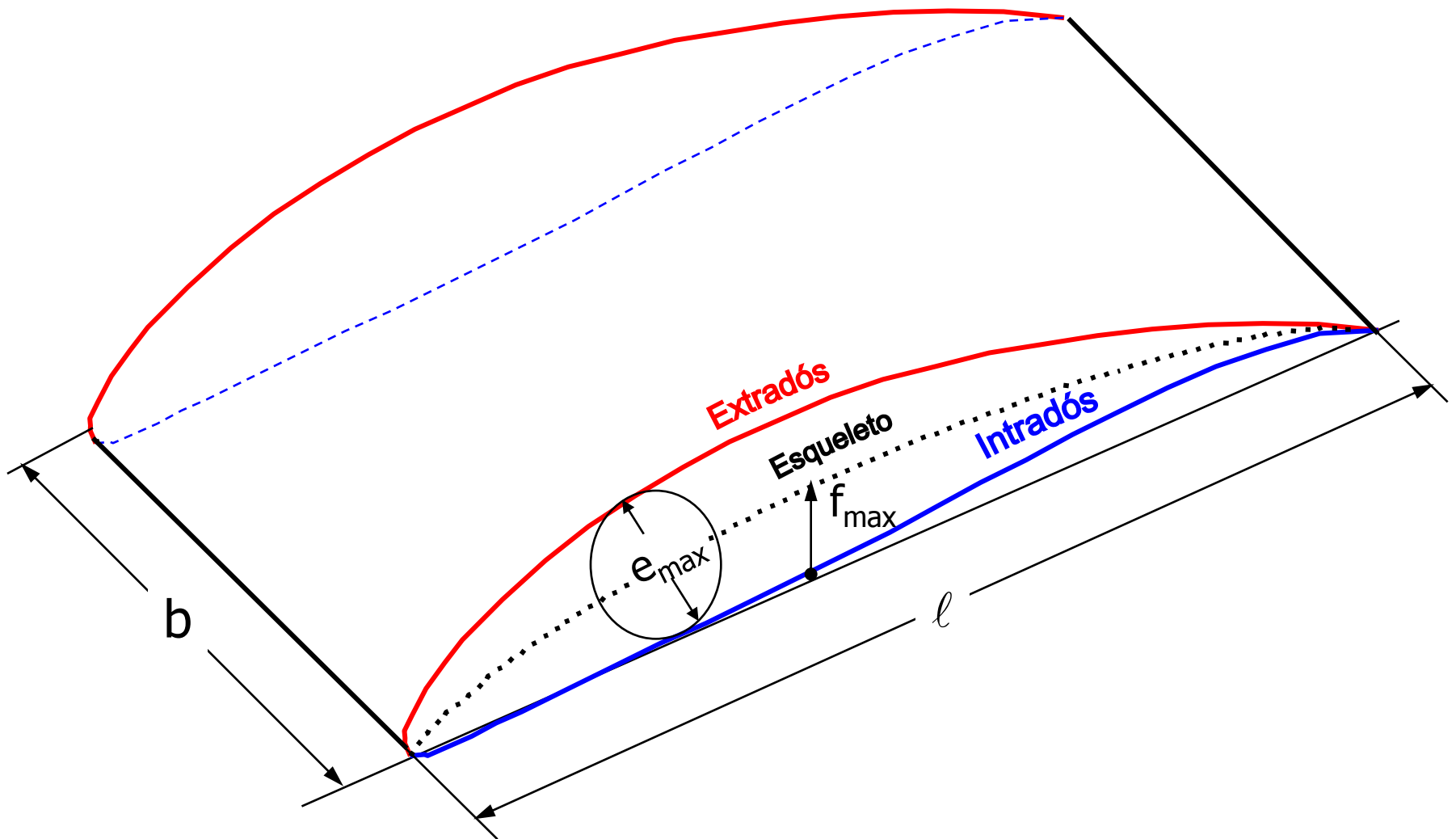
**Perfil Aislado y en Rejilla**

# Perfil Aerodinámico

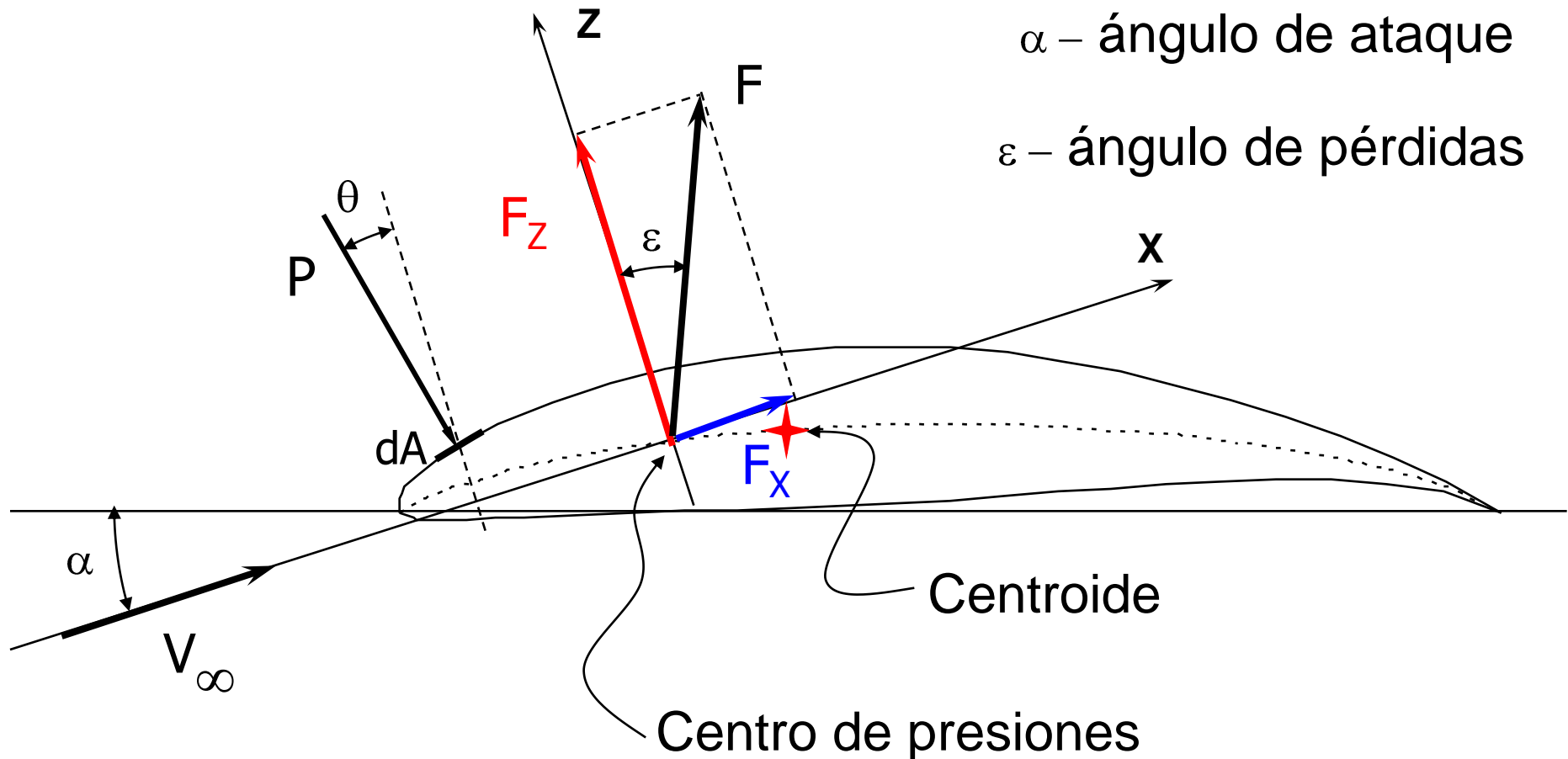
Perfil: Es un contorno cerrado, alargado en la dirección del flujo, el cual presenta un Borde de Ataque (BA) redondeado y Borde Fuga (BF) aguzado.



# Ala



# Perfil aislado portante





# Perfil aislado portante

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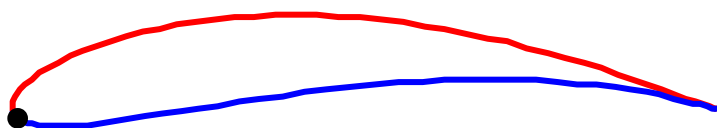
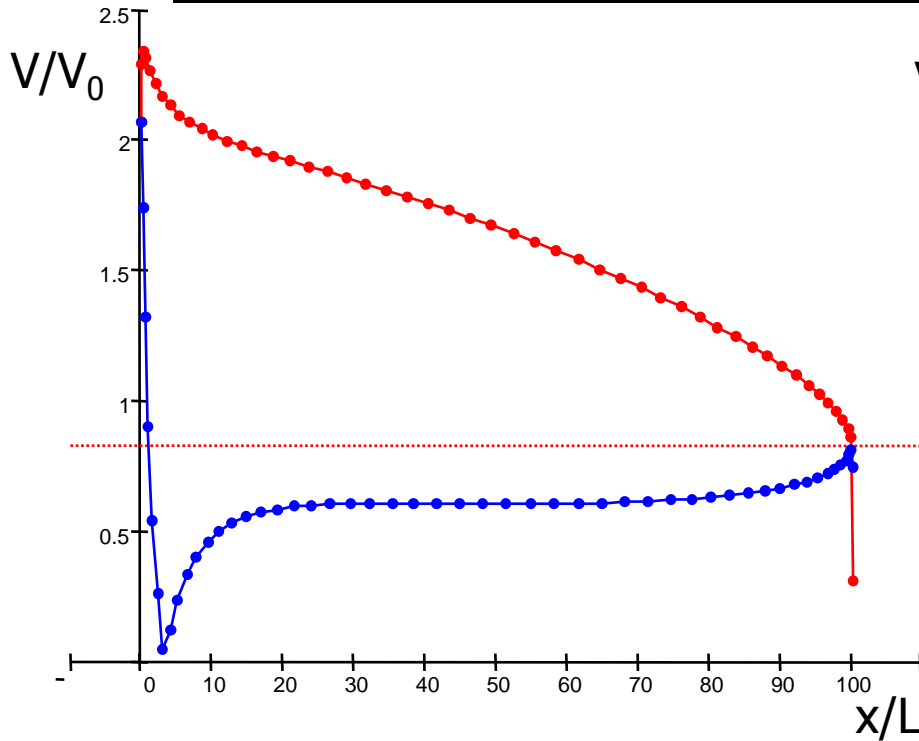
Las fuerzas de sustentación y de arrastre se calculan por integración del esfuerzo ejercido sobre la superficie del perfil por la distribución de presiones. Para un diferencial de área las fuerzas en la dirección OZ y OX se expresan por:

$$\begin{cases} dF_z = -P \cdot b \cdot dA \cdot \cos \theta \\ dF_x = P \cdot b \cdot dA \cdot \operatorname{sen} \theta \end{cases}$$

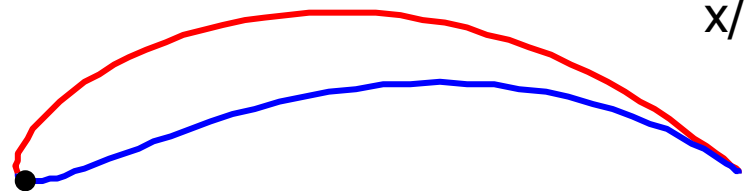
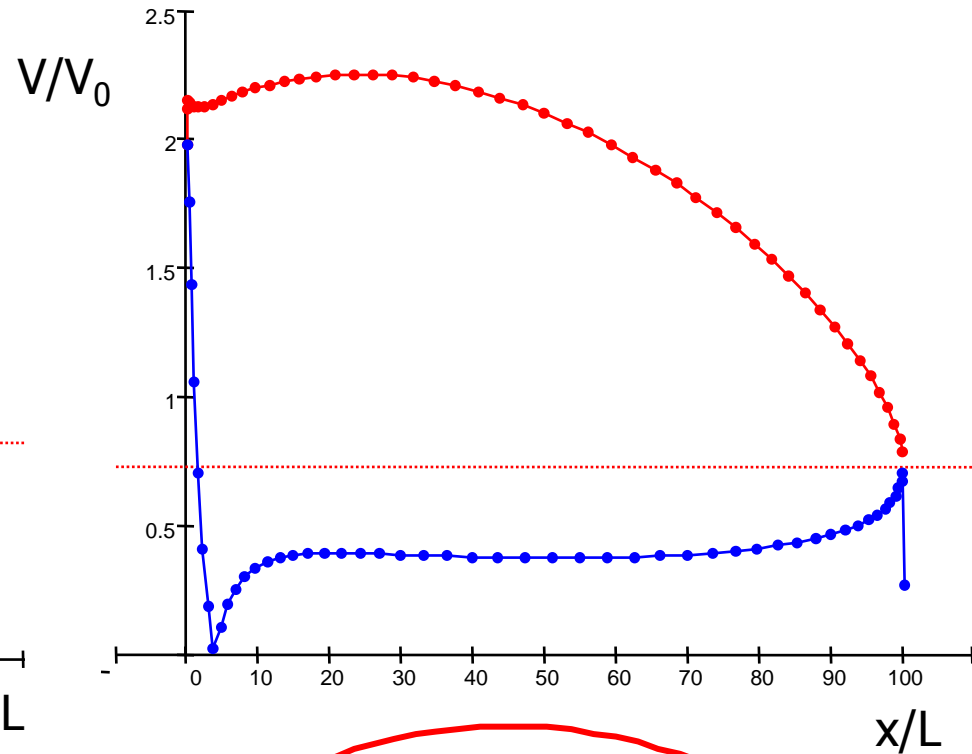
donde “b” es la envergadura del ala estudiada

# Distribución de Velocidades

## Efecto de la curvatura:



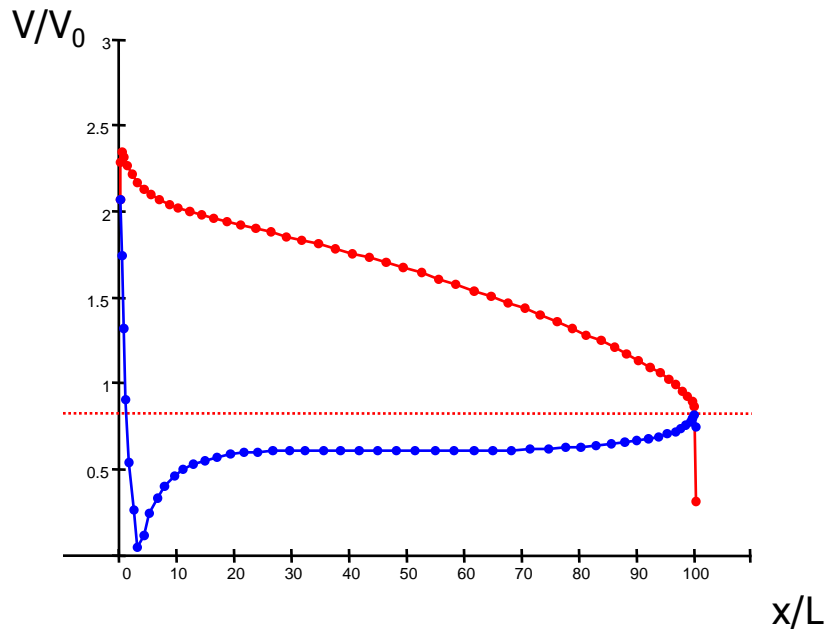
$$\alpha = 10^\circ, \beta = 10^\circ, k = 0,9$$



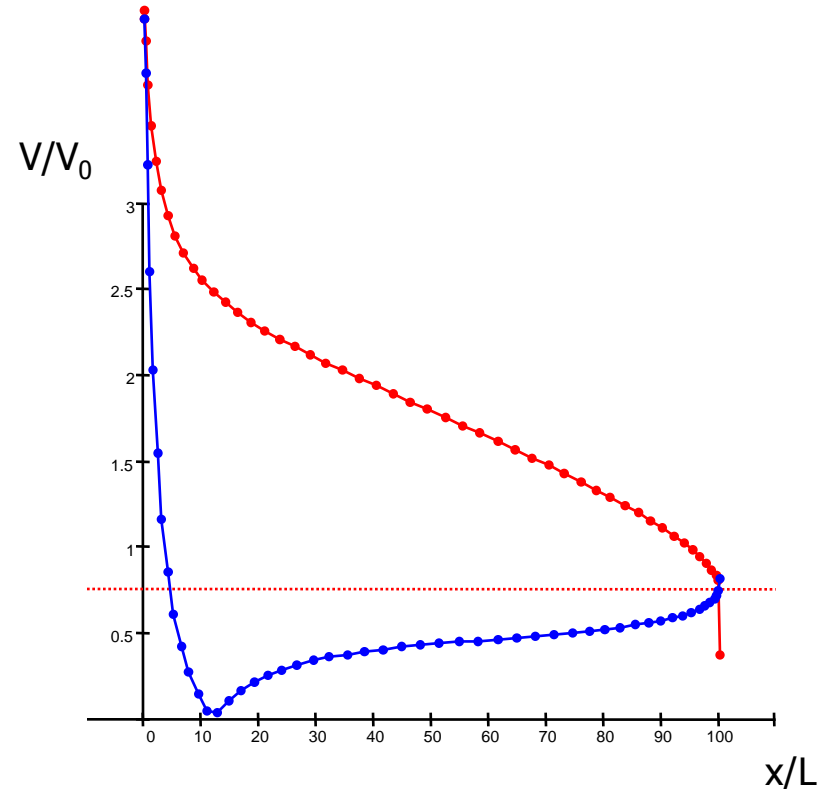
$$\alpha = 10^\circ, \beta = 20^\circ, k = 0,9$$

# Distribución de Velocidades

## Efecto de la ángulo de ataque:



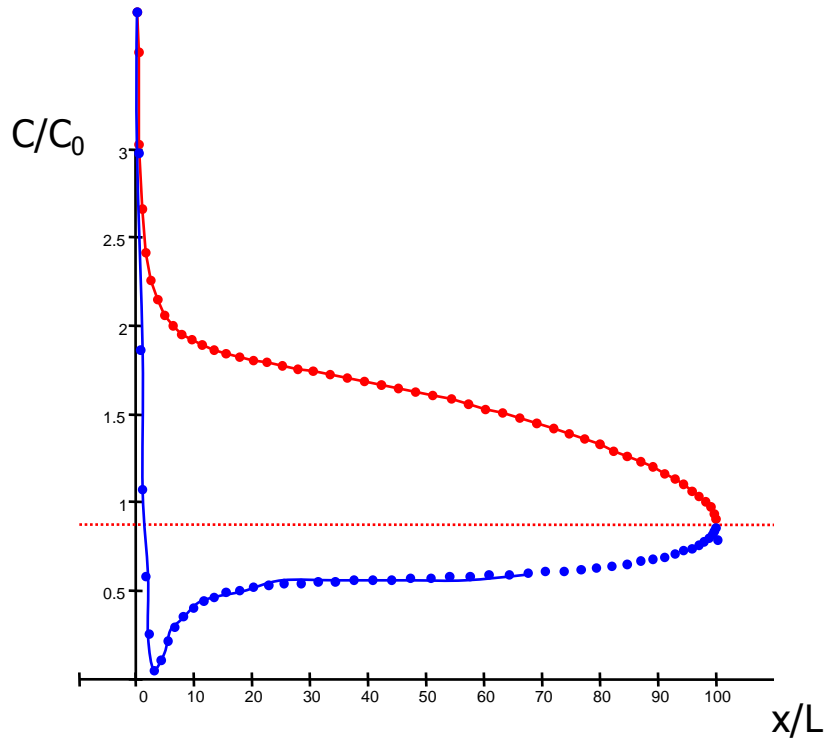
$\alpha = 10^\circ$ ,  $\beta = 10^\circ$ ,  $k = 0,9$



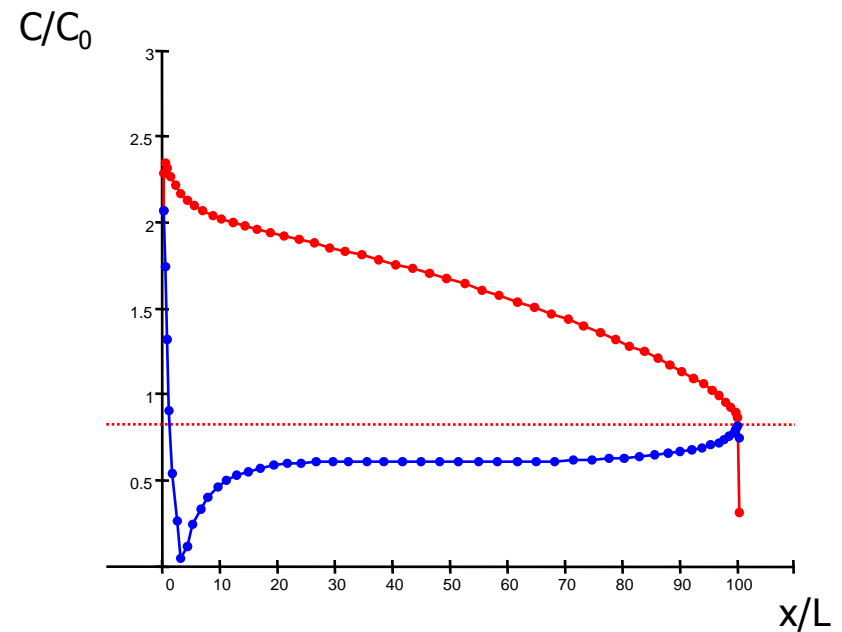
$\alpha = 20^\circ$ ,  $\beta = 10^\circ$ ,  $k = 0,9$

# Distribución de Velocidades

## Efecto del espesor relativo:



$$\alpha = 10^\circ, \beta = 10^\circ, k = 0,95$$

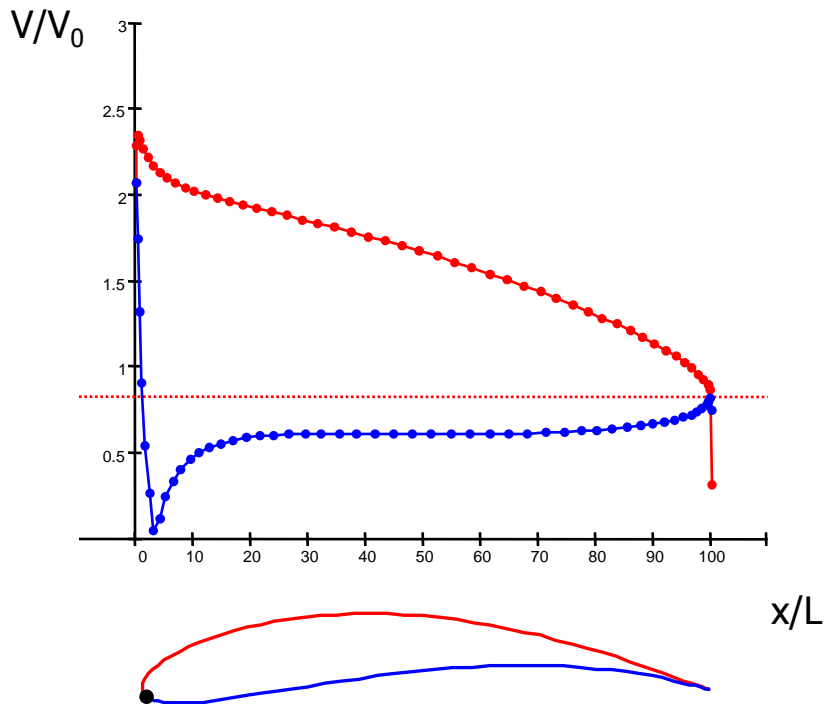


$$\alpha = 10^\circ, \beta = 10^\circ, k = 0,90$$

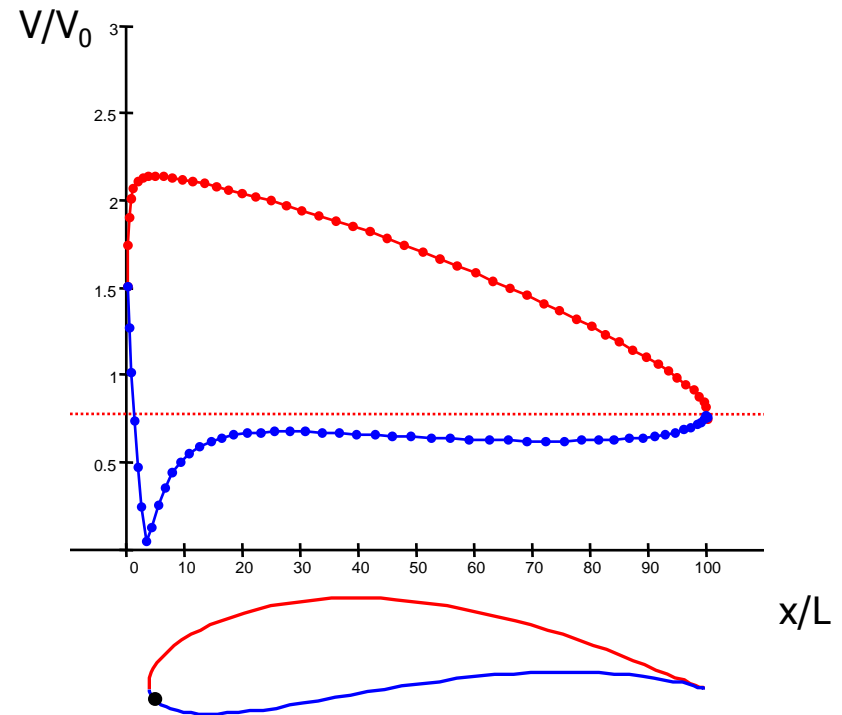


# Distribución de Velocidades

## Efecto del espesor relativo:



$$\alpha = 10^\circ, \beta = 10^\circ, k = 0,90$$



$$\alpha = 10^\circ, \beta = 10^\circ, k = 0,85$$



# Coeficientes

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Coeficiente de sustentación:

$$C_z = \frac{F_z / \ell}{\rho \cdot V_\infty^2 / 2}$$

Coeficiente de arrastre:

$$C_x = \frac{F_x / \ell}{\rho \cdot V_\infty^2 / 2}$$

Coeficiente de Momento:

(Referido al centroide)

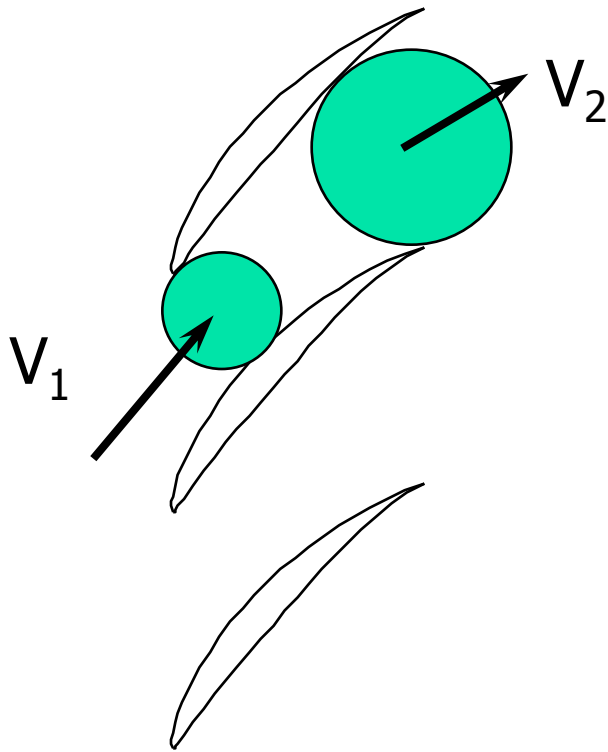
$$C_M = \frac{M / \ell^2}{\rho \cdot V_\infty^2 / 2}$$

Fineza Aerodinámica:

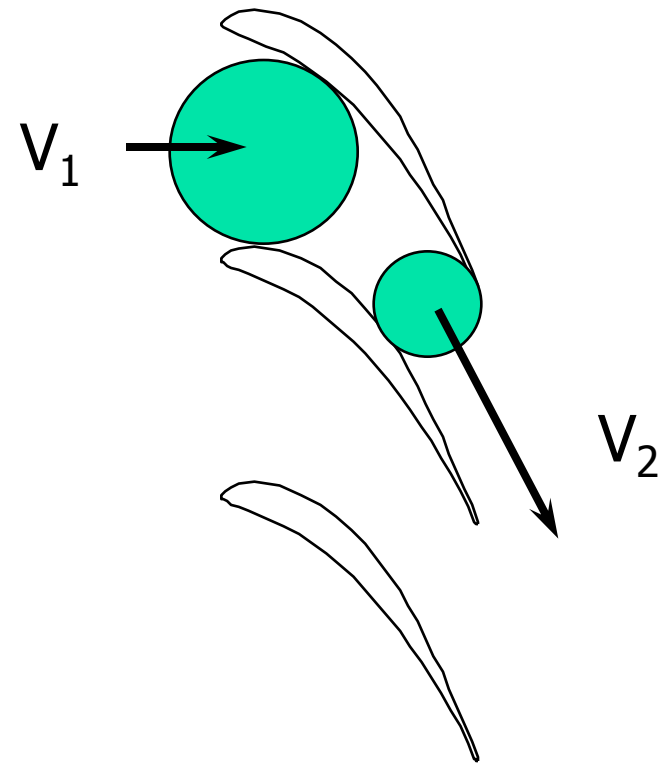
$$\text{ctg} \varepsilon = \frac{C_z}{C_x}$$

# Perfiles en rejilla

## 1. Tipos de Rejillas Planas :



Rejilla de Difusión



Rejilla de Aceleración

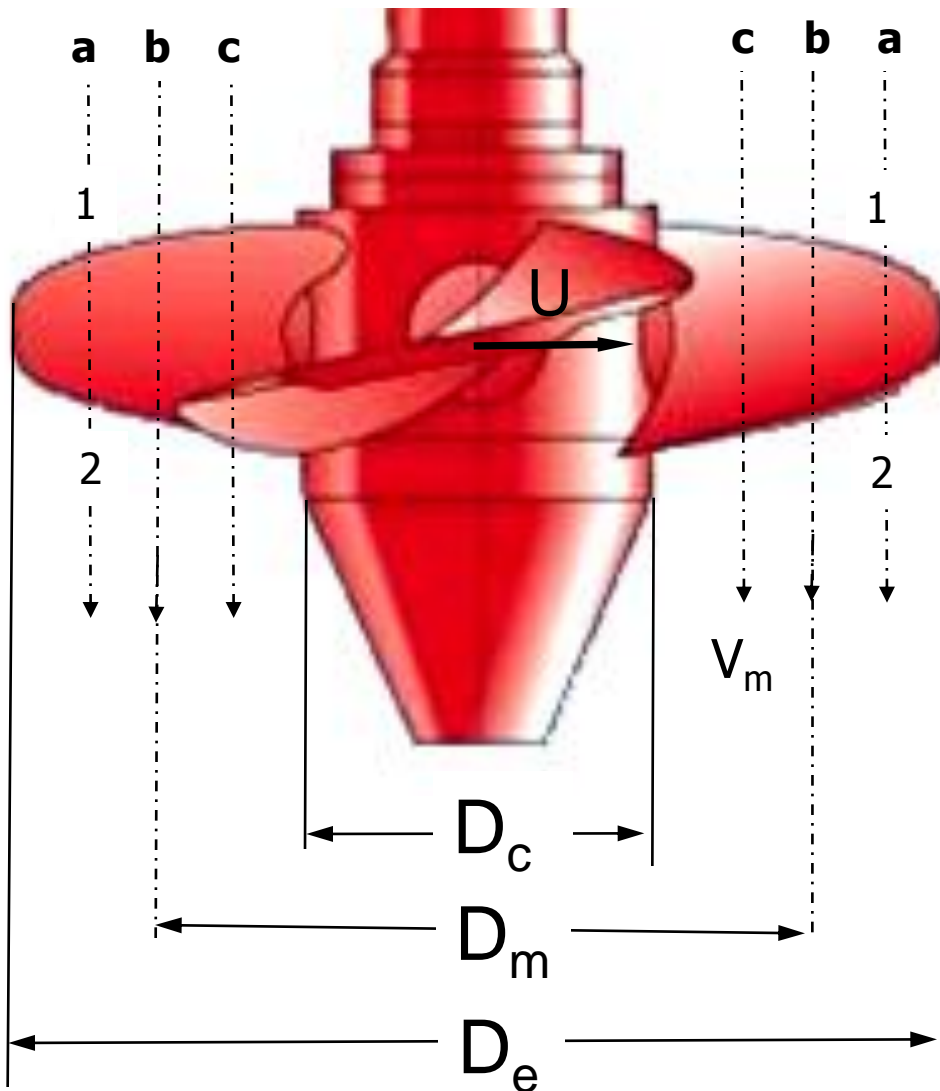


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## Transferencia de Energía

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$$V_R = 0$$

$$U_1 = U_2 = U$$

$$A_1 = A_2 = \frac{\pi}{4} \cdot (D_e^2 - D_c^2)$$

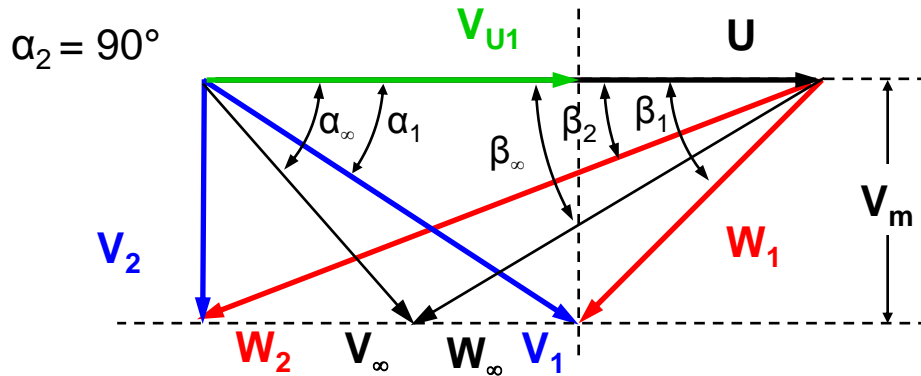
$$V_{m1} = V_{m2} = V_m$$

$$v = \frac{D_c}{D_e}$$

$$D_m = \frac{D_c + D_e}{2}$$

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## Triángulo de velocidades para $D = D_m$



$$\vec{V}_\infty = \vec{V}_{U\infty} + \vec{V}_{m\infty}$$

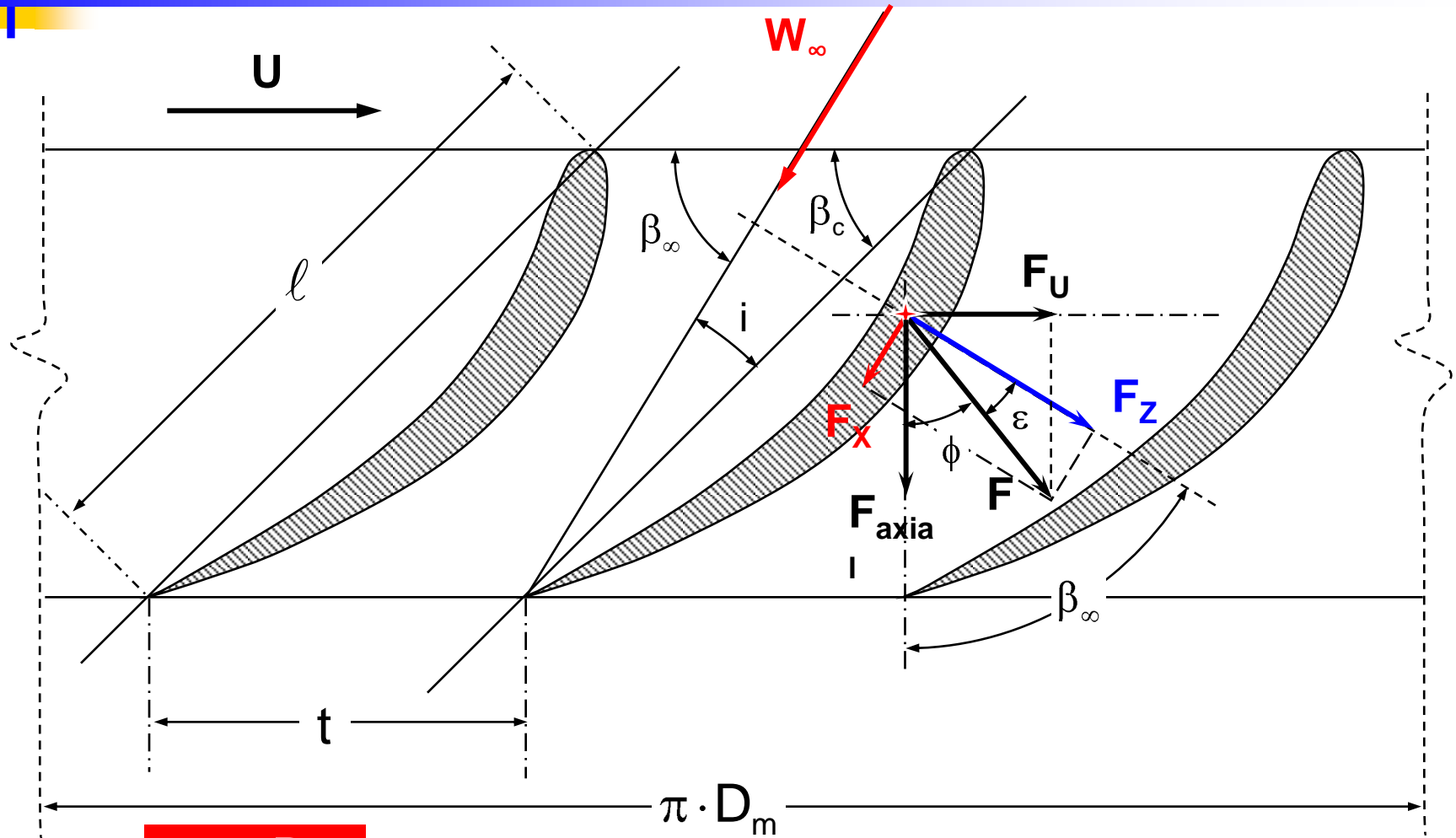
$$V_{U\infty} = \frac{V_{U1} + V_{U2}}{2} = \frac{V_{U1}}{2}$$

$$V_{m\infty} = V_m$$

$$H_t = \frac{U}{g} (V_{U1} - V_{U2})$$

Condición de diseño:  $\alpha_2 = 90^\circ \Rightarrow H_t = \frac{1}{g} U \cdot V_{U1}$

# Rejilla plana móvil



$$t = \frac{\pi \cdot D_m}{z}$$

$$i = \beta_\infty - \beta_c$$

$$\phi = \beta_\infty - \varepsilon$$

# Turbina Kaplan

Potencia:

$$P_{ot} = z \cdot F_U \cdot U = z \cdot F \cdot U \cdot \text{sen}\phi = z \cdot F \cdot U \cdot \text{sen}(\beta_\infty - \varepsilon)$$

$$F = \frac{F_z}{\text{COS}\varepsilon}$$

$$F_z = C_z \rho \frac{W_\infty^2}{2} \ell \cdot b$$



$$P_{ot} = z \cdot b \cdot C_z \cdot \ell \cdot \rho \frac{W_\infty^2}{2} U \cdot \frac{\text{sen}(\beta_\infty - \varepsilon)}{\text{COS}\varepsilon}$$

$$b = \frac{D_e - D_c}{2} \quad (\text{envergadura del alabe})$$

Empuje axial:

$$F_{axial} = z \cdot C_z \rho \frac{W_\infty^2}{2} \ell \cdot b \cdot \frac{\text{cos}(\beta_\infty - \varepsilon)}{\text{COS}\varepsilon}$$





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Caudal:

$$Q = A \cdot V_m$$

$$A = \frac{\pi}{4} (D_e^2 - D_c^2) = \pi \cdot D_m \cdot b$$

$$b = \frac{D_e - D_c}{2}$$

$$t = \frac{\pi \cdot D_m}{z}$$


$$Q = z \cdot t \cdot b \cdot V_m$$



# Turbina Kaplan

Altura H transferida a la turbina:

$$H_t = \frac{P_{ot}}{\rho \cdot g \cdot Q} = \frac{z \cdot b \cdot C_z \cdot \ell \cdot \rho \frac{W_\infty^2}{2} U \cdot \frac{\text{sen}(\beta_\infty - \varepsilon)}{\text{cos} \varepsilon}}{\rho \cdot g \cdot z \cdot t \cdot b \cdot V_m}$$

$$H_t = \frac{1}{2g} \cdot C_z \cdot \frac{\ell}{t} \cdot \frac{W_\infty^2 \cdot U}{V_m} \cdot \frac{\text{sen}(\beta_\infty - \varepsilon)}{\text{cos} \varepsilon}$$

Ec. Fundamental de las TBMH axiales



# Turbina Kaplan

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## Eficiencia Hidráulica:

$$\varepsilon = 0 \rightarrow H = \frac{1}{2g} \cdot C_z \cdot \frac{\ell}{t} \cdot W_\infty \cdot U \quad \text{sen}\beta_\infty = \frac{V_m}{W_\infty}$$

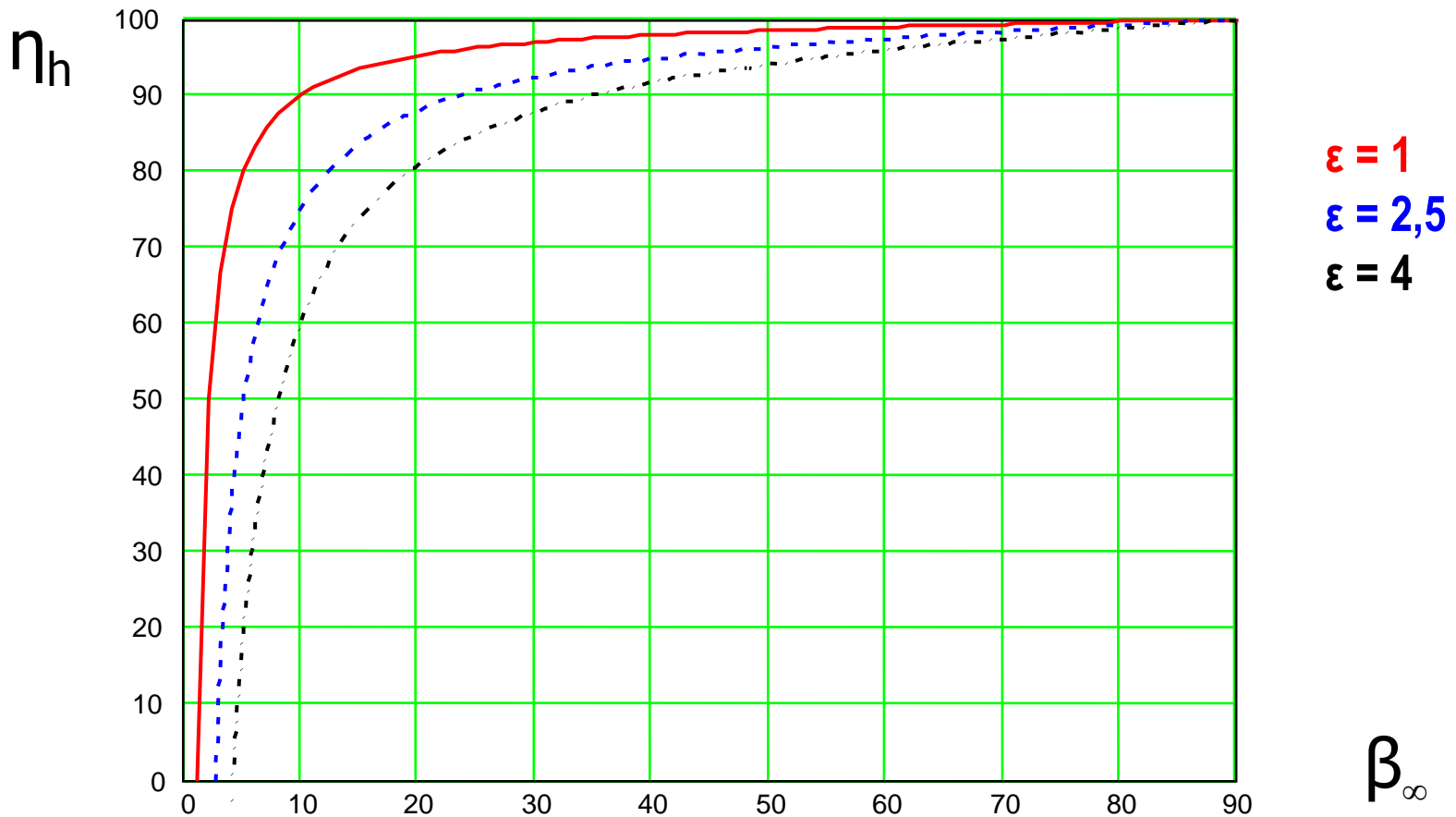
$$\eta_h = \frac{H_t}{H} = \frac{\text{sen}(\beta_\infty - \varepsilon)}{\text{sen}\beta_\infty \cdot \text{cos}\varepsilon} = 1 - \frac{\text{cos}\beta_\infty \cdot \text{sen}\varepsilon}{\text{sen}\beta_\infty \cdot \text{cos}\varepsilon}$$

$$\eta_h = 1 - \frac{\text{tg}\varepsilon}{\text{tg}\beta_\infty}$$

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Eficiencia Hidráulica:

$$\eta_h = 1 - \frac{\operatorname{tg}\varepsilon}{\operatorname{tg}\beta_\infty}$$



$\beta_\infty$

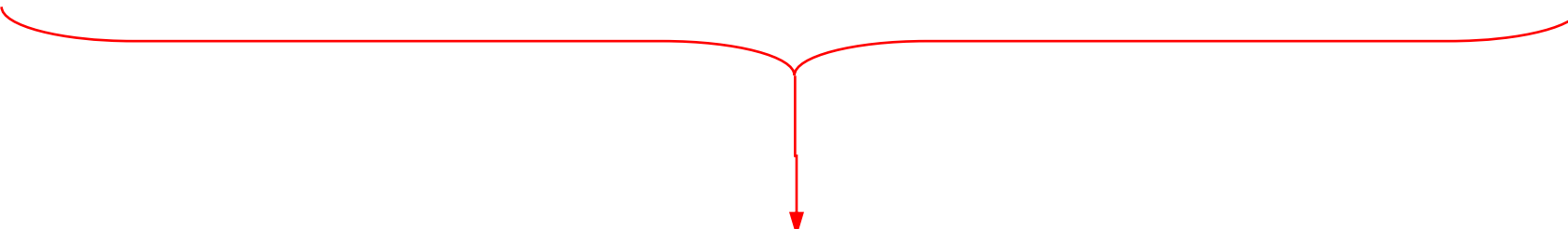
# Turbina Kaplan

Velocidad específica de giro  $n_s$

$$P_m = \eta \frac{\rho g \cdot Q \cdot H}{A}$$

$$Q = \frac{\pi}{4} D_e^2 (1 - v^2) \cdot V_m$$

$$\operatorname{tg} \beta_2 = \frac{V_m}{U_{2e}}$$


$$n_s = \sqrt{\eta \frac{\rho}{A}} \cdot \frac{60 \cdot 2^{1/4} g^{5/4}}{\sqrt{\pi}} \cdot K_{U_{1m}} \cdot \sqrt{(1 - v^2) \cdot K_{U_{2e}}} \cdot \sqrt{\operatorname{tg} \beta_2} \cdot \frac{D_e}{D_m}$$



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Velocidad específica de giro  $n_s$

$$\beta_2 = 14^\circ$$

$$g = 9,81 \text{ m/s}^2$$

$$\rho = 997 \text{ kg/m}^3$$

$$A = 735,3$$

$$\eta = 0,90$$

$$n_s \cong 386 \cdot K_{U1} \cdot \sqrt{(1 - v^2)} \cdot K_{U2e} \cdot \frac{D_e}{D_m}$$

$$K_{U1} \uparrow, K_{U2} \uparrow \frac{D_e}{D_m} \uparrow, v \downarrow \Rightarrow n_s \uparrow$$



# Turbina Kaplan

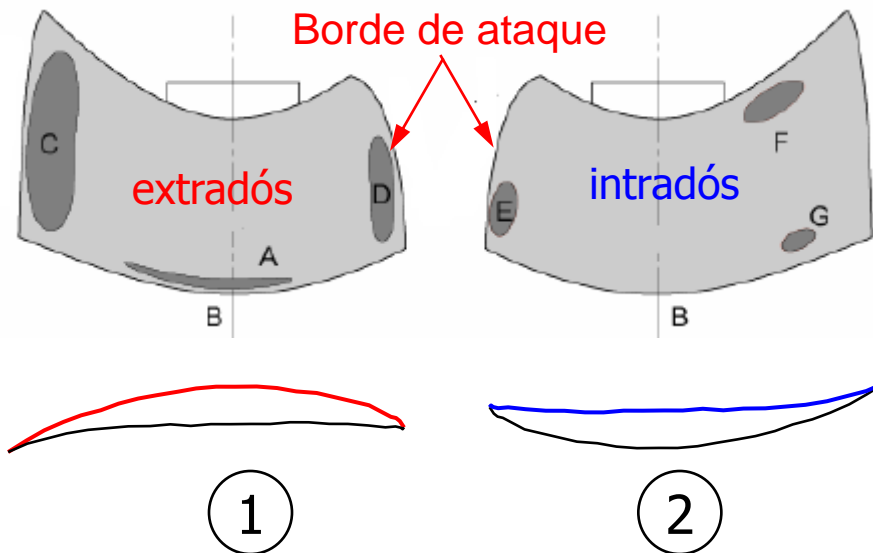
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## Cavitación

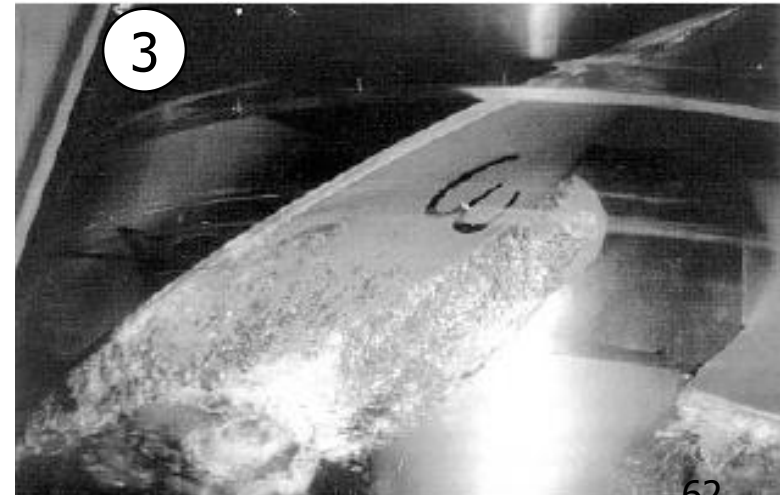
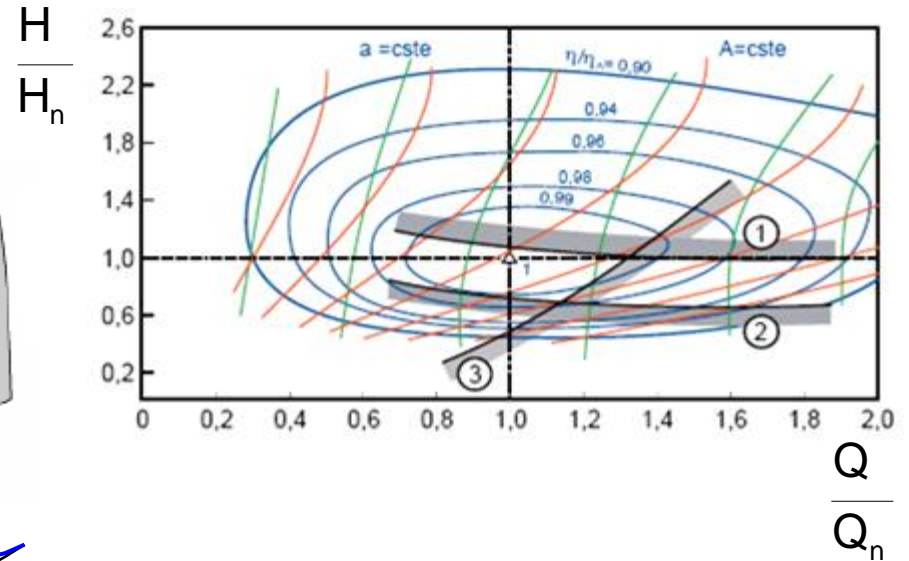


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## Zonas de erosión



1. Límite Cavitación en el borde de ataque, extradós (zona D).
2. Límite Cavitación en el borde de ataque, intradós (zona E).
3. Límite de cavitación en el cubo.



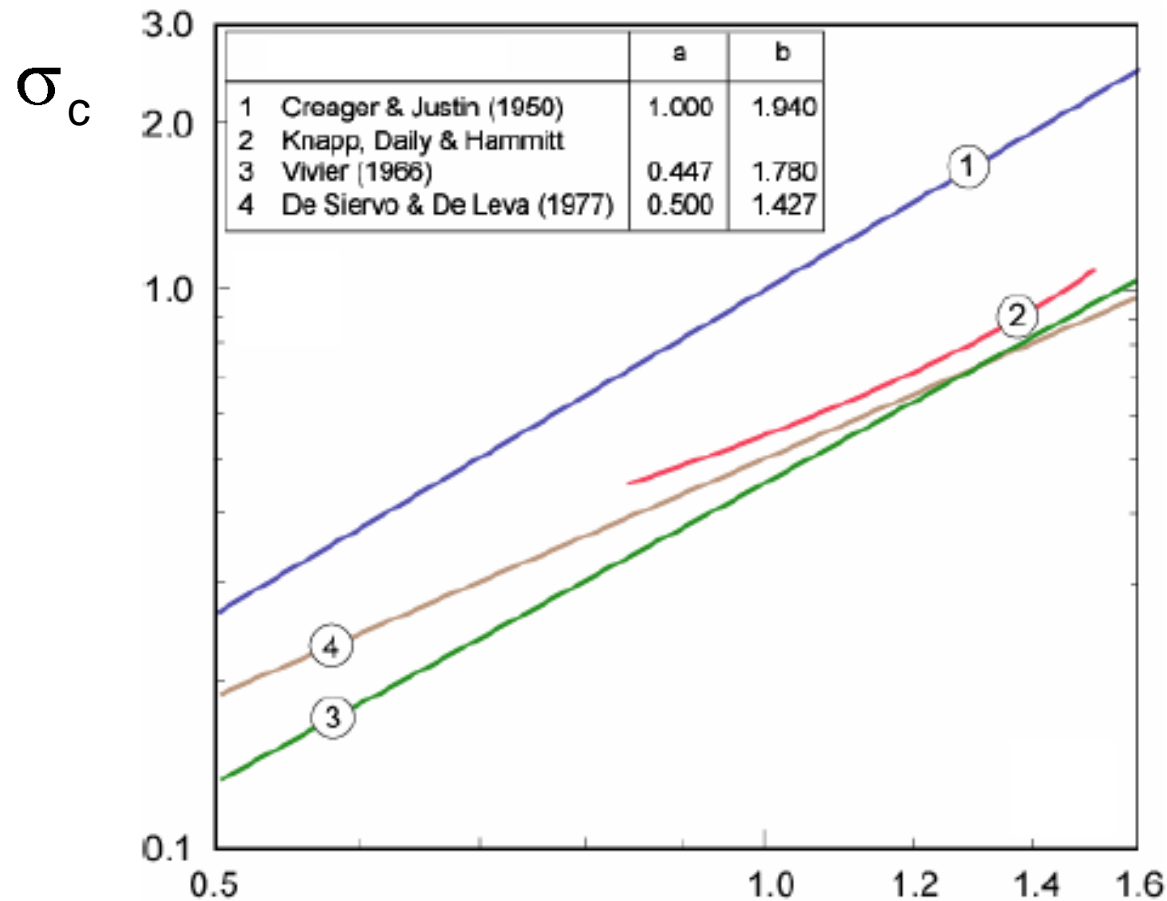
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Cavitación (vórtice en el extremo del alabe)



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Valores del número de Thoma Crítico



$$\sigma_c = a \cdot \Omega^b$$

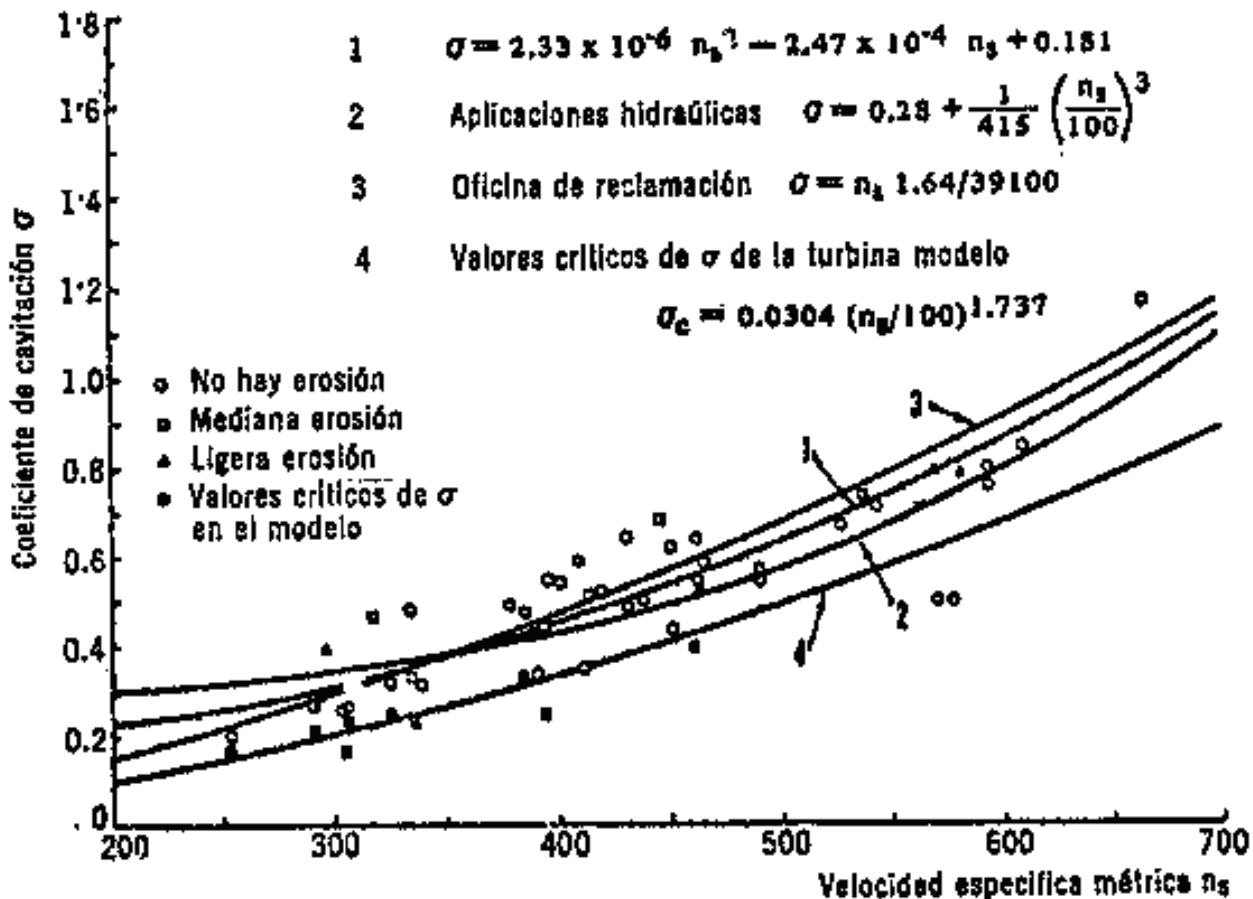
$$\Omega = \frac{\omega \sqrt{P_m}}{(gH)^{5/4}}$$

$\Omega$

# Turbina Kaplan

## Valores del número de Thoma Crítico

$$\sigma_c = 0,0304 \cdot \left( \frac{n_s}{100} \right)^{1,737}$$





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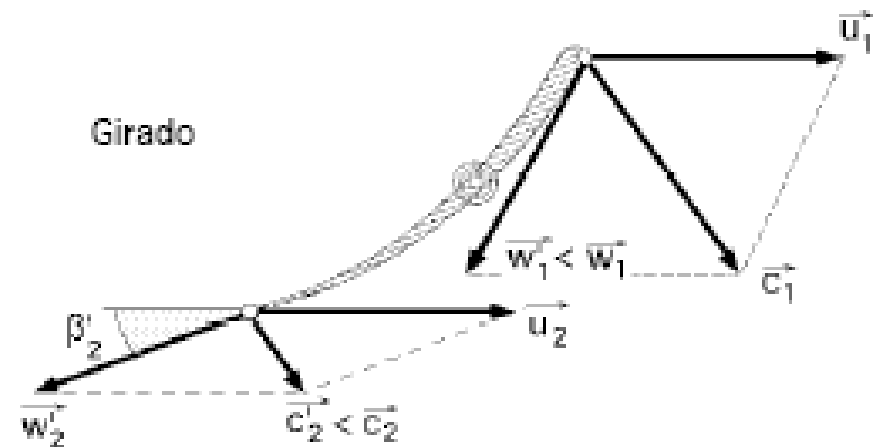
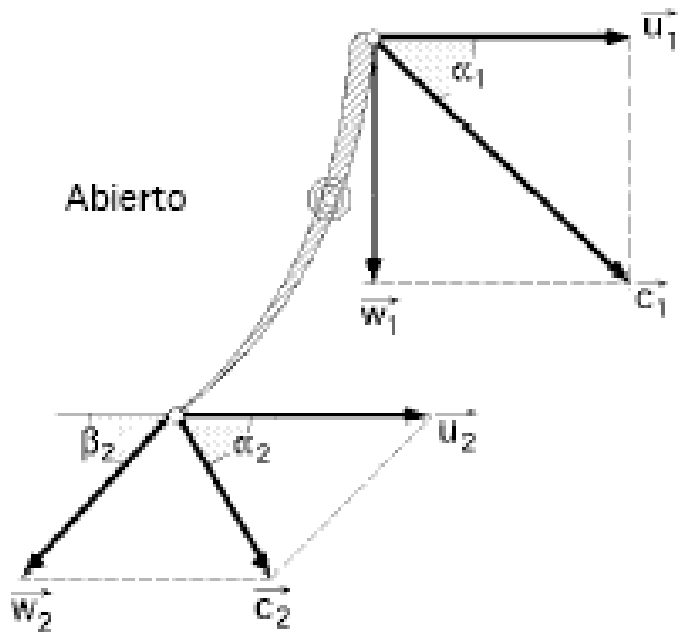
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## Operación

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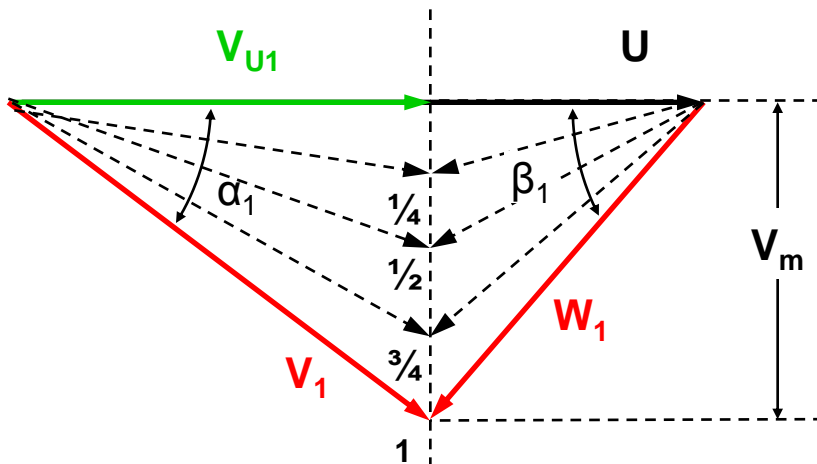
## Principio de la Doble Regulación TK

*Triángulos en el rodete*

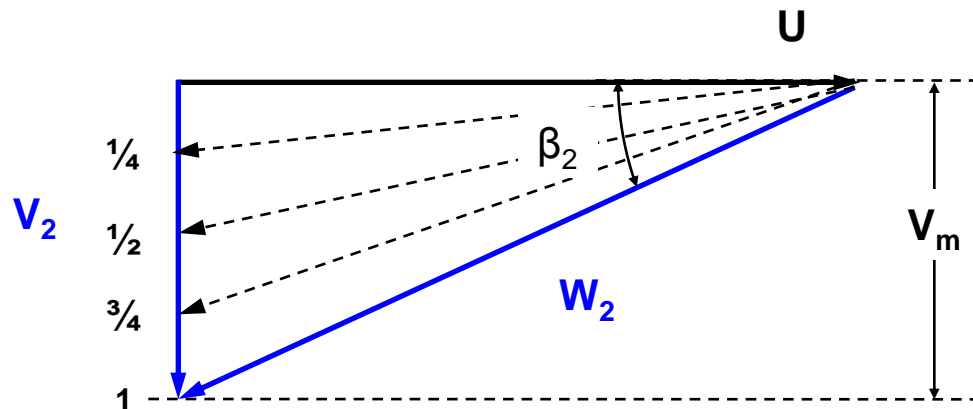


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## Principio de la Doble Regulación TK



$$i = \beta_{\infty} - \beta_c = \text{cte.}$$

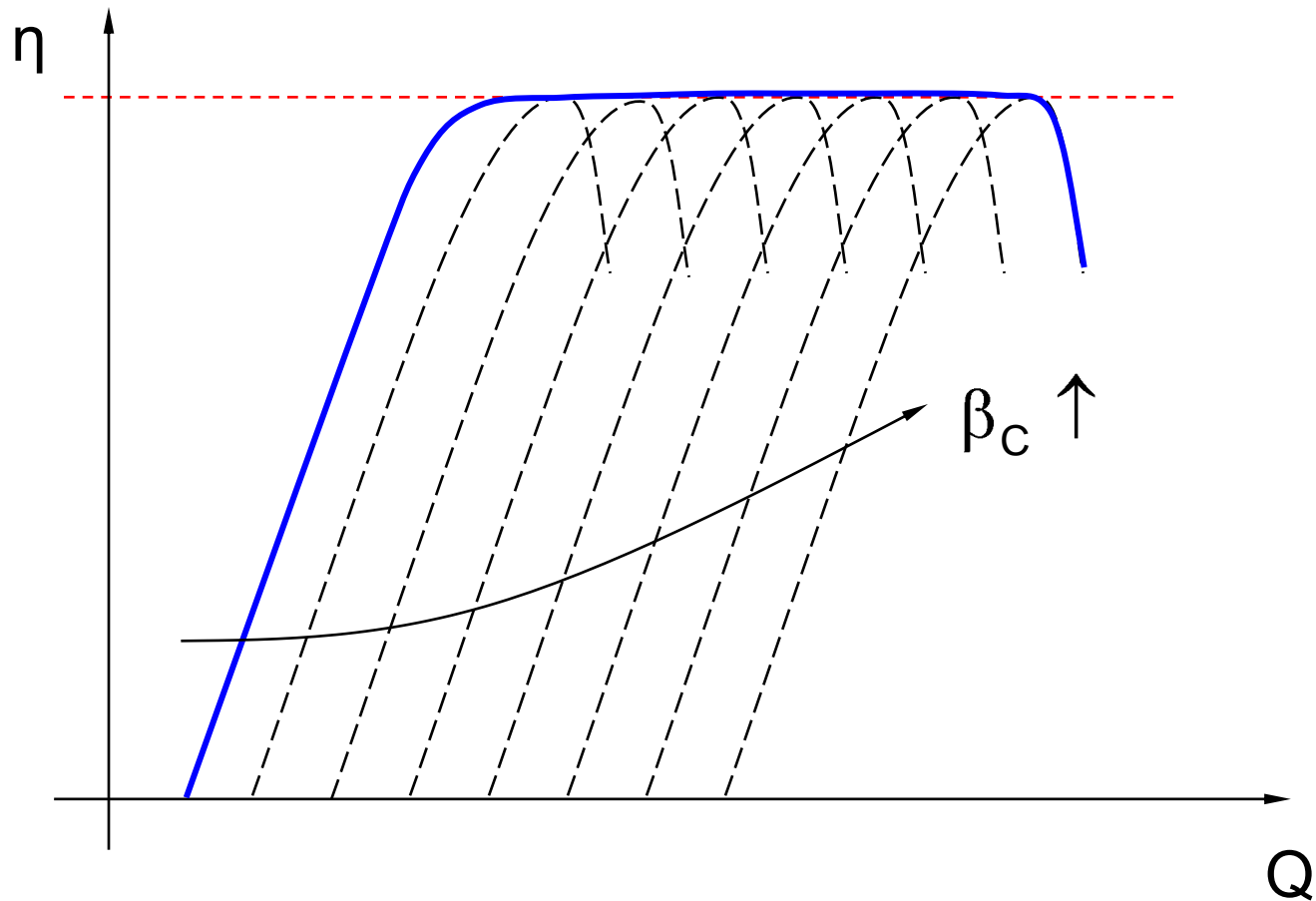


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## Doble Regulación TK

$n = \text{cte}$

$H = \text{cte}$





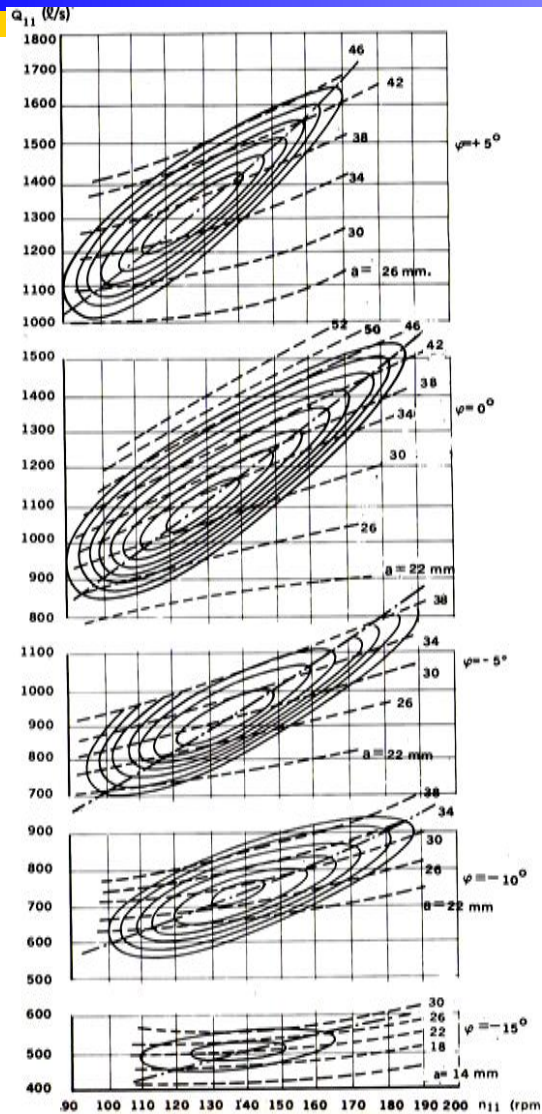


# **Turbina Kaplan**

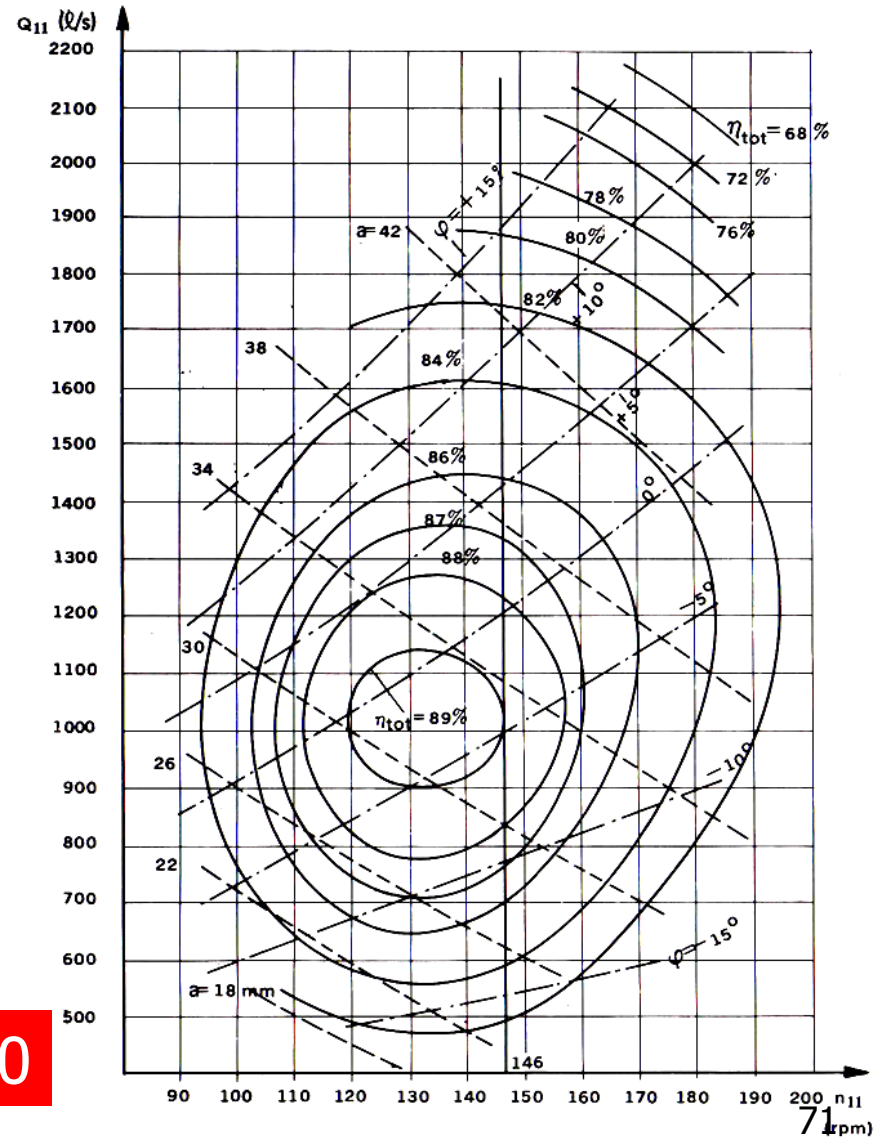
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## **Curvas Características**

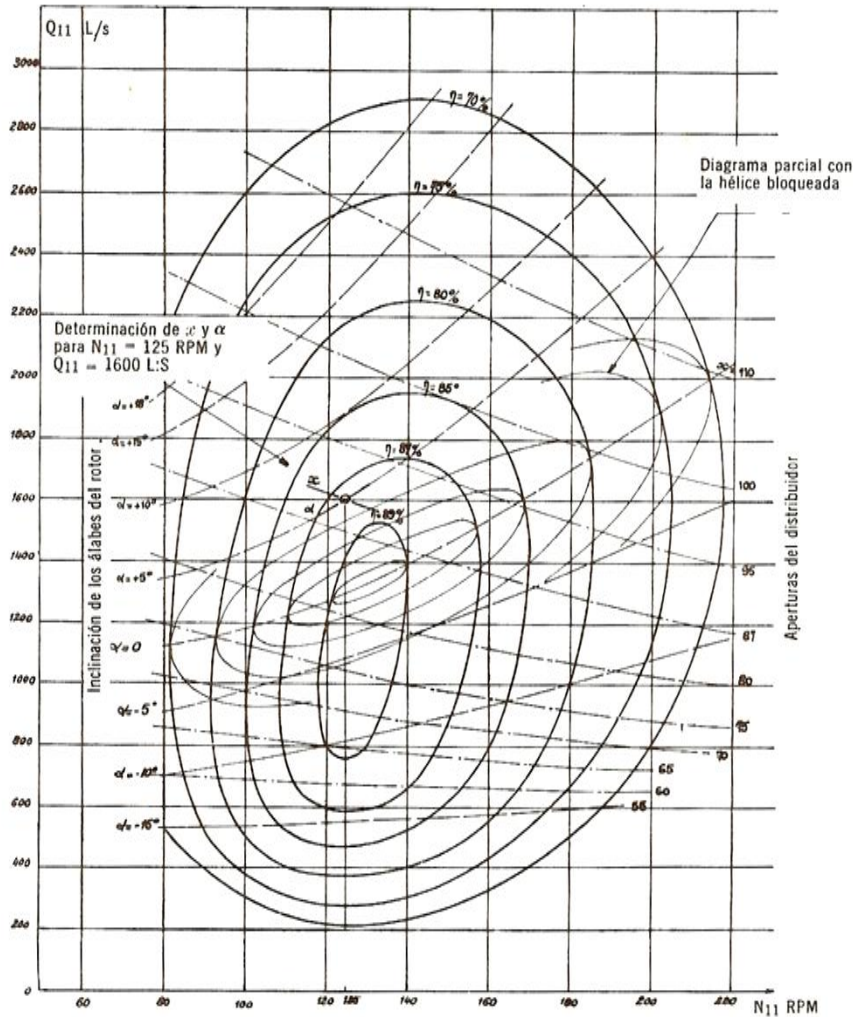
# Construcción del Diagrama Topográfico



$n_s = 450$



# Diagrama Topográfico



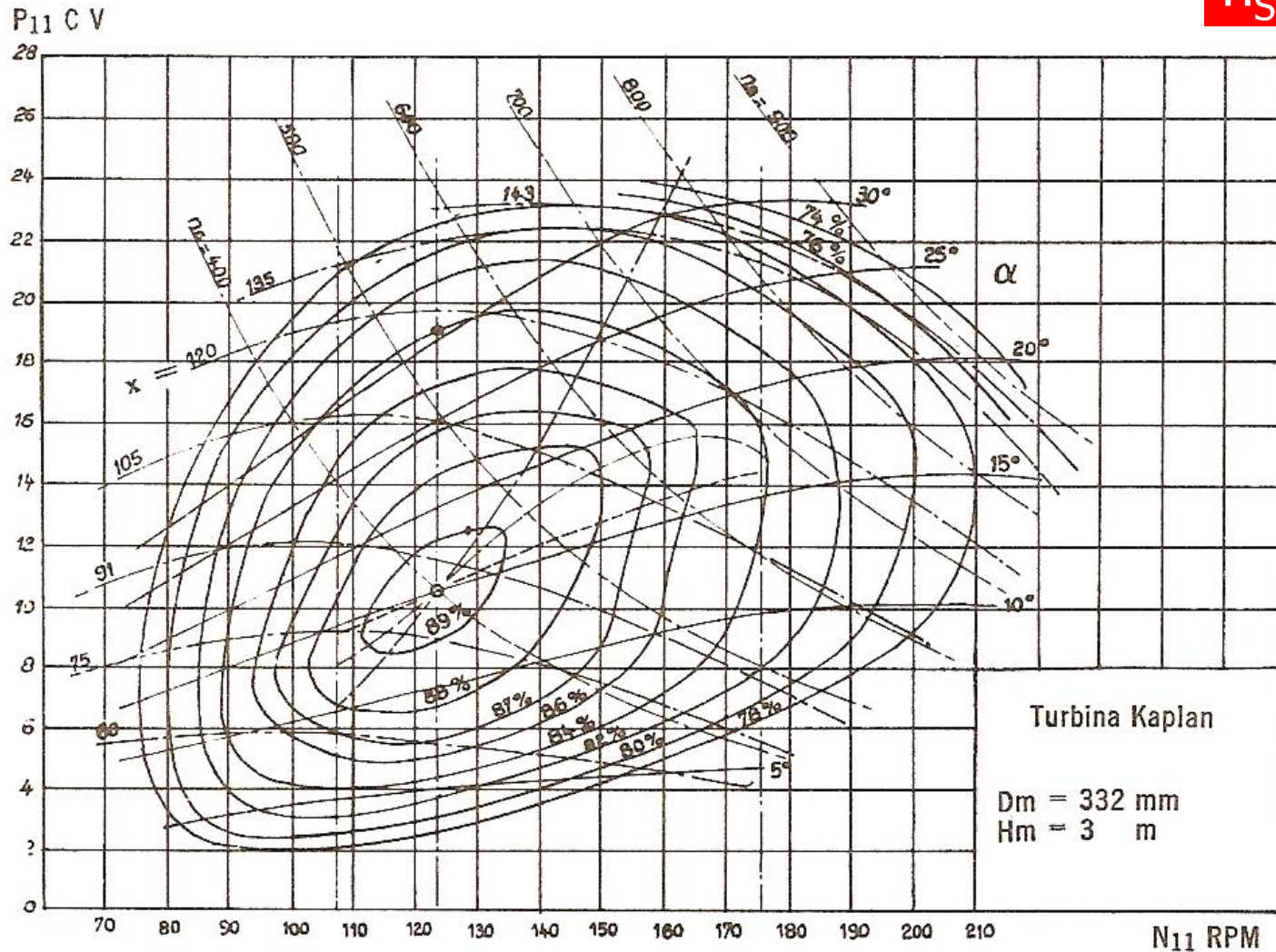
$$n_s = 500$$

$$N_{11}^n = 135$$

$$Q_{11}^n = 1,20$$

# Diagrama Topográfico

$n_s = 400$





# Turbina Kaplan

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## Dimensionamiento

# Dimensionamiento Estadístico

**Cálculo del número específico de revoluciones según Siervo:**

Año de diseño	ns
1960-1964	$2096 \cdot H_n^{-0.489}$
1965-1969	$2195 \cdot H_n^{-0.489}$
1970-1975	$2419 \cdot H_n^{-0.489}$

$$n_s = \frac{\text{rpm} \sqrt{Kw}}{m^{5/4}}$$

**Calculo del número de Thoma:**

$$\sigma_{ins} = \frac{B - H_s - H_v}{H_n}$$

$$\sigma_c = 6,35 \cdot 10^{-5} \cdot n_s^{1.46}$$

# Dimensionamiento del Rodete

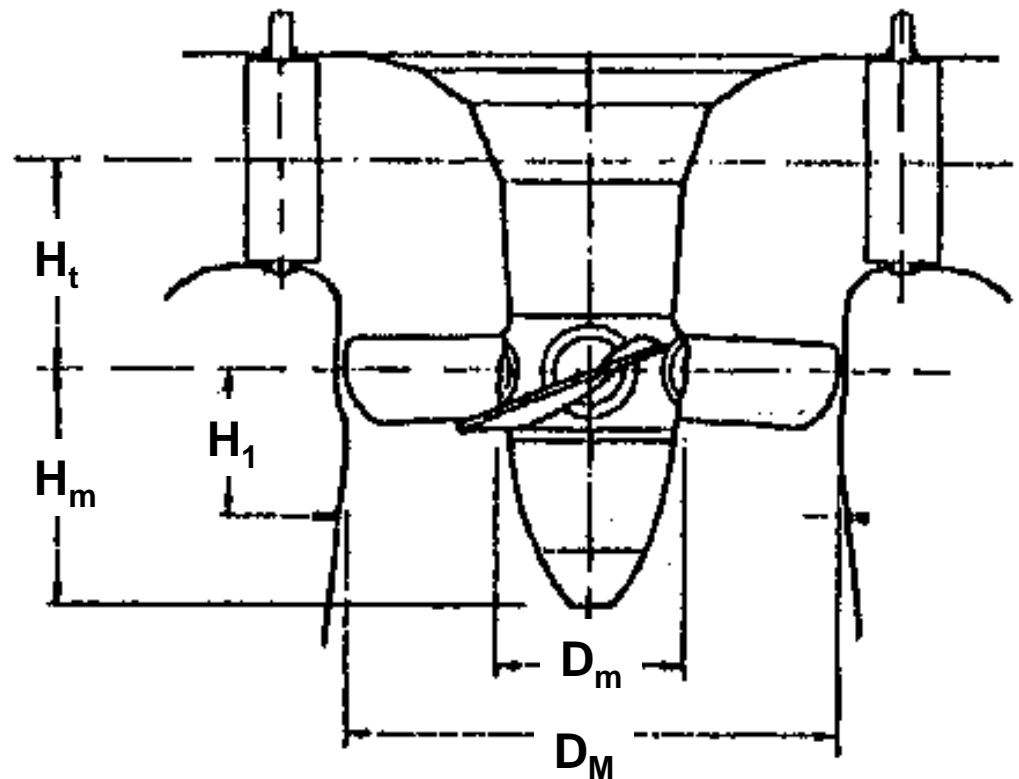
$$K_U = 0,79 + 1,61 \cdot 10^{-3} n_s$$

$$D_M = 84,5 \cdot K_U \frac{\sqrt{H_n}}{n}$$

$$\frac{D_m}{D_M} = 0,25 + \frac{94,5}{n_s}$$

$$\frac{H_m}{D_M} = 6,94 \cdot n_s^{-0.403}$$

$$\frac{H_1}{D_M} = 0,38 + 5,17 \cdot 10^{-5} \cdot n_s$$







# Dimensionamiento Caja Espiral

$$\frac{A}{D_M} = 0,40 \cdot n_s$$

$$\frac{B_1}{D_M} = 1,26 + 3,79 \cdot 10^{-4} n_s$$

$$\frac{B_2}{D_M} = \frac{1}{0,76 + 8,92 \cdot 10^{-5} \cdot n_s}$$

$$\frac{C_1}{D_M} = 1,46 + 3,24 \cdot 10^{-4} \cdot n_s$$

$$\frac{C_2}{D_M} = \frac{1}{0,55 + 1,48 \cdot 10^{-5} \cdot n_s}$$

$$\frac{D_1}{D_M} = 1,59 + 5,74 \cdot 10^{-4} \cdot n_s$$

$$\frac{D_2}{D_M} = \frac{1}{1,58 + 9,05 \cdot 10^{-5} \cdot n_s}$$

$$\frac{E_1}{D_M} = 1,21 + 2,71 \cdot 10^{-4} \cdot n_s$$

$$\frac{E_2}{D_M} = \frac{1}{1,48 + 2,11 \cdot 10^{-5} \cdot n_s}$$

$$\frac{F_1}{D_M} = 1,21 + \frac{72,17}{n_s}$$

$$\frac{F_2}{D_M} = 1,62 - 3,18 \cdot 10^{-5} \cdot n_s$$





# Dimensionamiento Caja Espiral

$$\frac{G_1}{D_M} = 1,29 + \frac{41,63}{n_s}$$

$$\frac{G_2}{D_M} = 1,36 + \frac{7,79}{n_s}$$

$$\frac{H_1}{D_M} = 1,13 + \frac{31,86}{n_s}$$

$$\frac{H_2}{D_M} = 1,19 + \frac{4,69}{n_s}$$

$$\frac{I_1}{D_M} = 0,45 - \frac{31,80}{n_s}$$

$$\frac{I_2}{D_M} = 0,44 - \frac{21,4}{n_s}$$

$$\frac{L_1}{D_M} = 0,74 + 8,7 \cdot 10^{-4} \cdot n_s$$

$$\frac{L_2}{D_M} = 1,44 + \frac{105,29}{n_s}$$

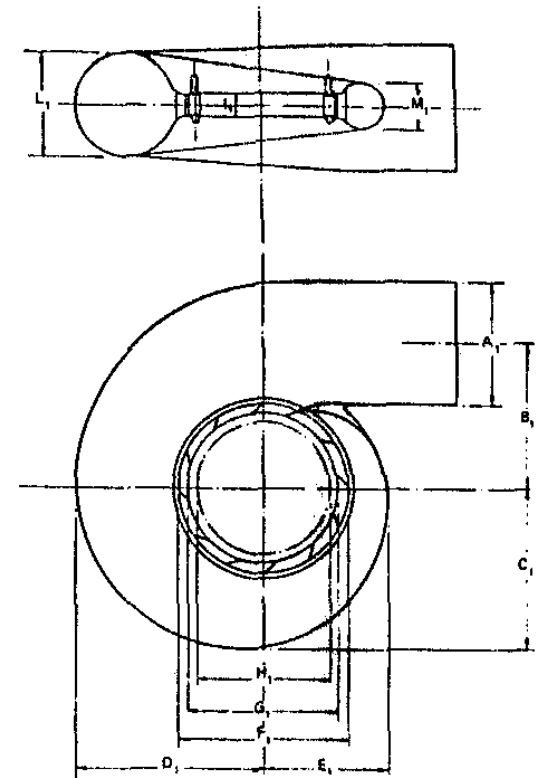
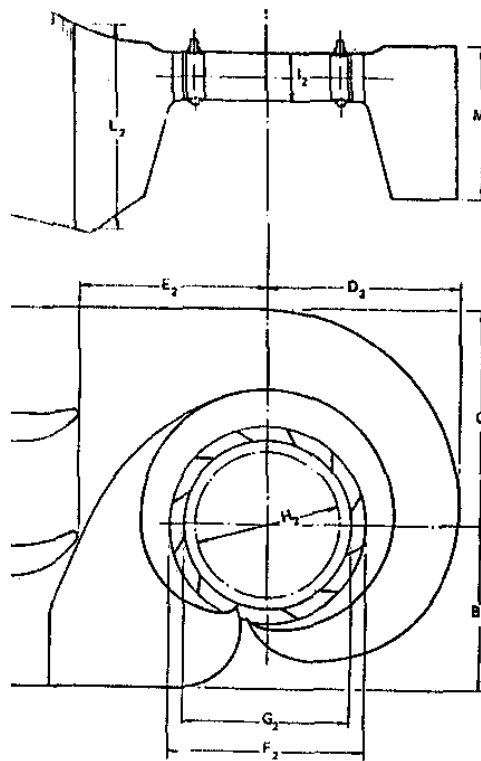
$$\frac{M_1}{D_M} = \frac{1}{2,06 - 1,20 \cdot 10^{-3} \cdot n_s}$$

$$\frac{M_2}{D_M} = 1,03 + \frac{136,28}{n_s}$$

# Dimensionamiento Caja Espiral

Espesor de la caja espiral:

Material	Espesor
acero	$B_1 + C_1 + \frac{A_1}{2} = 3,76 \cdot D_M$
concreto	$B_2 + C_2 = 3,04 \cdot D_M$



# Tubo de Aspiración

$$\frac{H_t}{D_M} = 0,24 + 7,82 \cdot 10^{-5} \cdot n_s$$

$$\frac{N}{D_M} = 2,00 - 2,14 \cdot 10^{-6} \cdot n_s$$

$$\frac{O}{D_M} = 1,40 - 1,67 \cdot 10^{-5} \cdot n_s$$

$$\frac{P}{D_M} = 1,26 - \frac{16,35}{n_s}$$

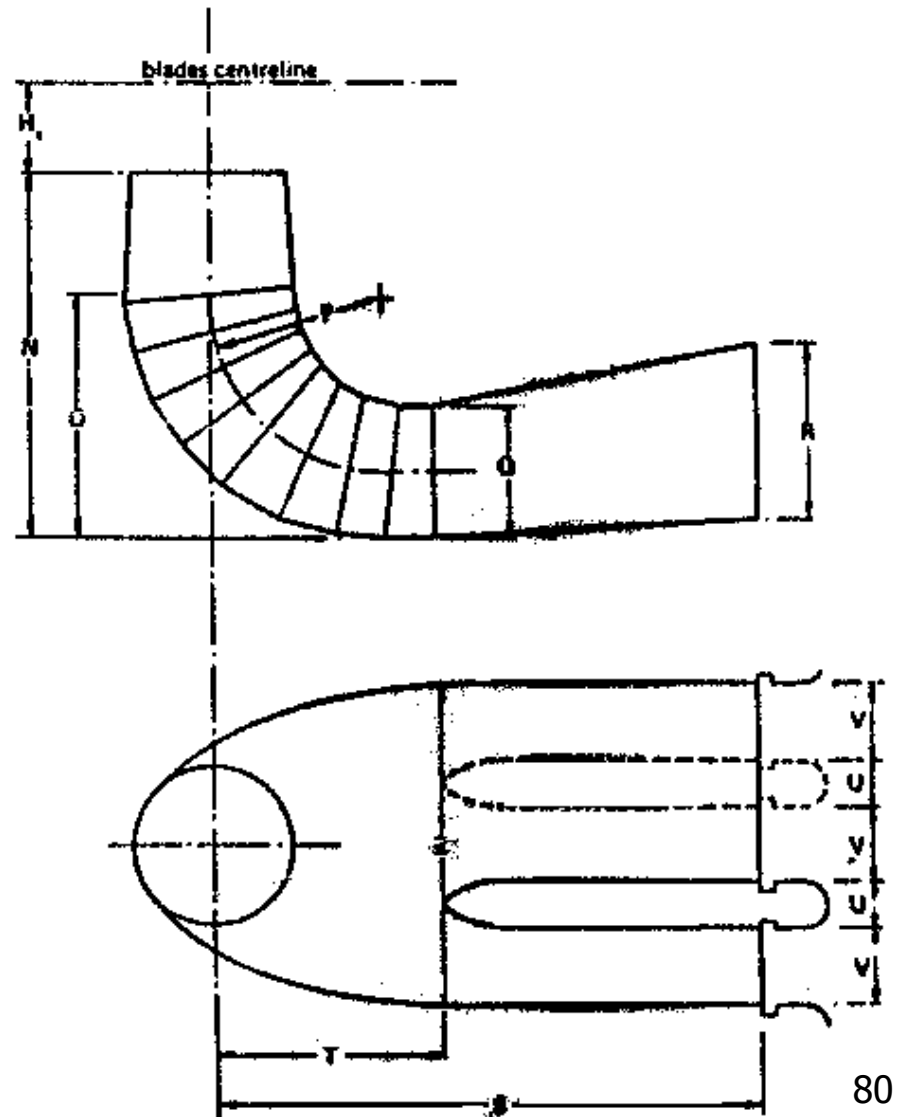
$$\frac{Q}{D_M} = 0,66 - \frac{18,40}{n_s}$$

$$\frac{R}{D_M} = 1,25 - 7,98 \cdot 10^{-5} \cdot n_s$$

$$\frac{S}{D_M} = 4,26 + \frac{201,51}{n_s}$$

$$\frac{T}{D_M} = 1,20 + 5,12 \cdot 10^{-4} \cdot n_s$$

$$\frac{Z}{D_M} = 2,58 + \frac{102,66}{n_s}$$





# **Turbinas Kaplan**

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## **Instalaciones en Venezuela**

# Bajo Caroní

## Central Caruachi



$D = 9,0 \text{ m}$

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### Turbinas

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Número

12

$H_n$

35,6 m

Pot. nominal

180 MW

n

94,74 rpm

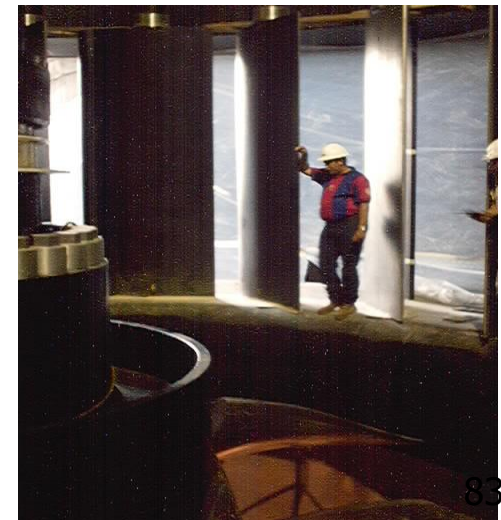
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Pot. central

2160 MW

# Bajo Caroní

## Central Caruachi







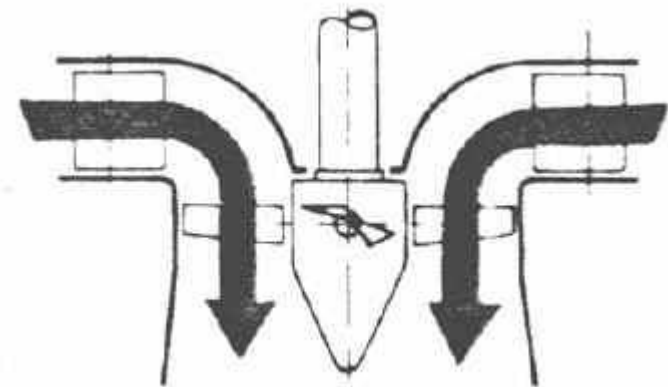
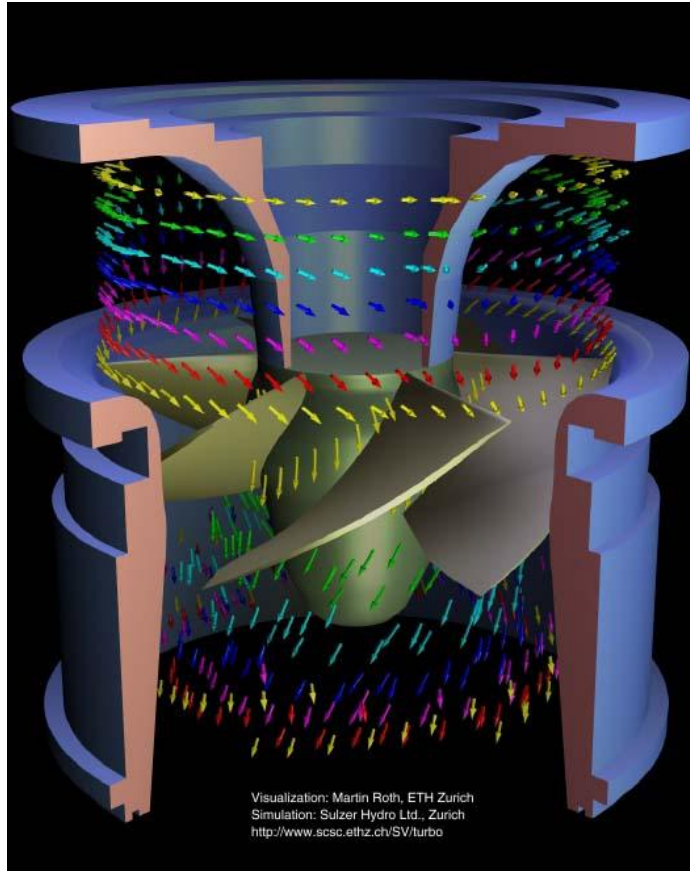
# Bajo Caroní

## Central Macagua II.

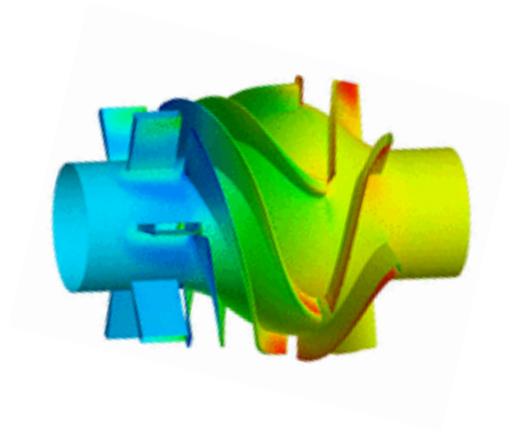
<b>TURBINAS</b>	<b>Casa de Máquinas 3</b>
Número	2
Tipo	Kaplan
Elevación anillo distribuidor	24 m.s.n.m.
Caída neta nominal	22.6 m
Caída neta máxima	23 m
Velocidad nominal	94.74 rpm
Velocidad de embalamiento	230 rpm
Velocidad específica	564
Caudal nominal	415 m <sup>3</sup> /s
Capacidad nominal	86 MW
Capacidad máxima	88,2 MW

# Flujo en el Rotor

Simulación CFD  
del Rotor







# ***Turbinas Kaplan***

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***FIN***