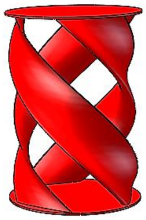
به نام خدا

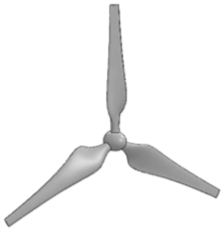
مقدمه ای بر توربوماشین های تراکم ناپذیر
(پمپ- فن- توربین آبی- توربین باد و توربین جریان اقیانوسی)

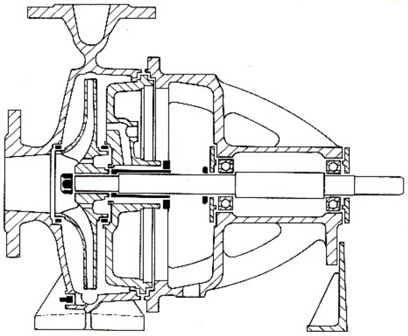
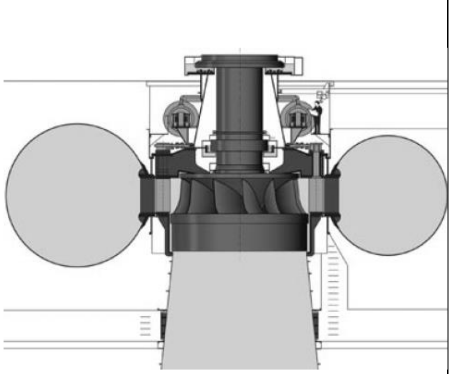
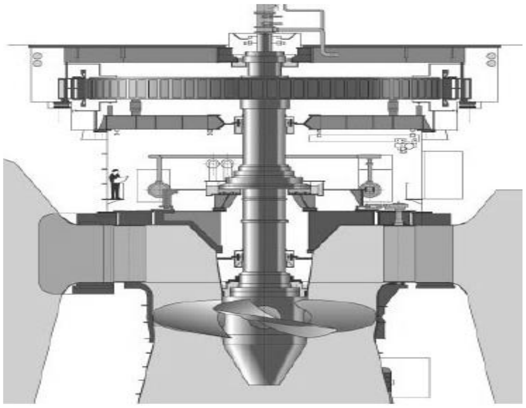
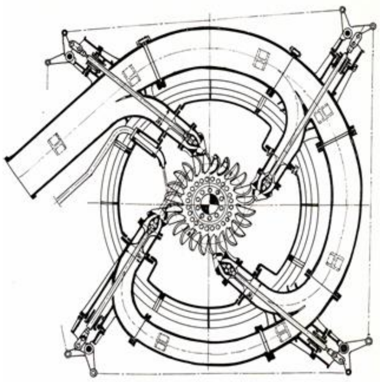
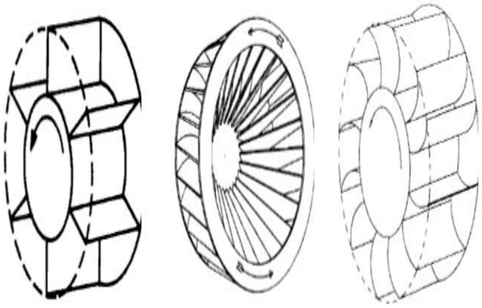
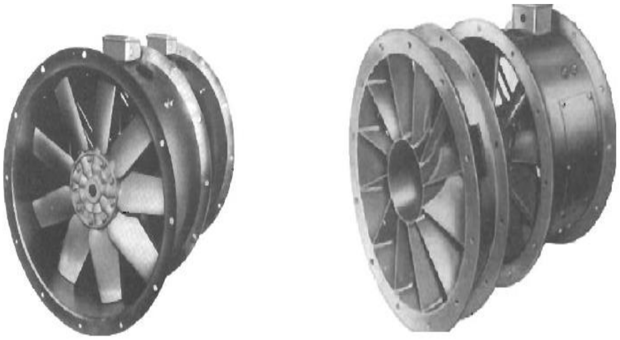
ویرایش سوم

دکتر علیرضا ریاسی
دانشکده مهندسی مکانیک
دانشگاه تهران

پاییز ۱۳۹۶





INCOMPRESSIBLE FLOW TURBOMACHINES			
PUMPS			
HYDRAULIC			
FANS			
WIND TURBINES			

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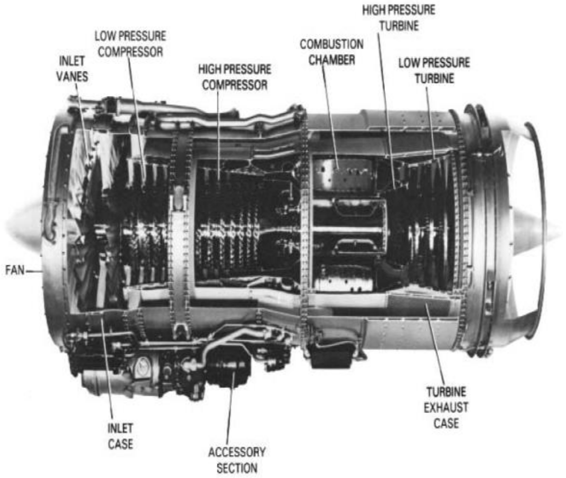
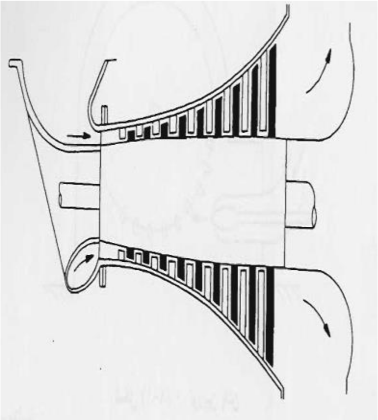
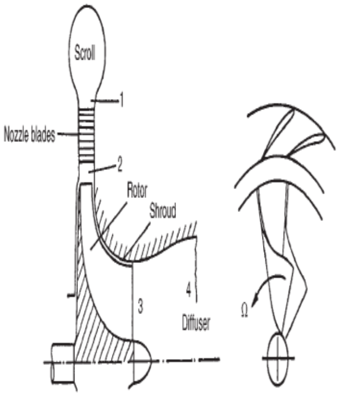
<tr><td>GAS TURBINES</td><td>
</td><td></td><td>
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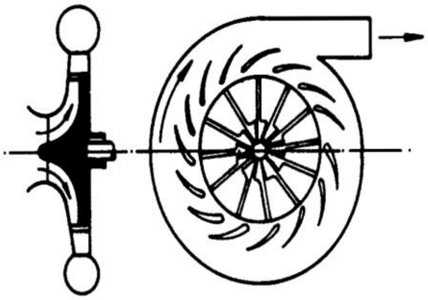
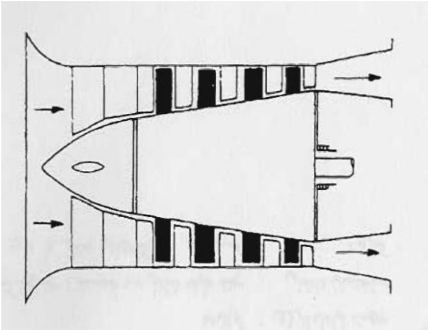
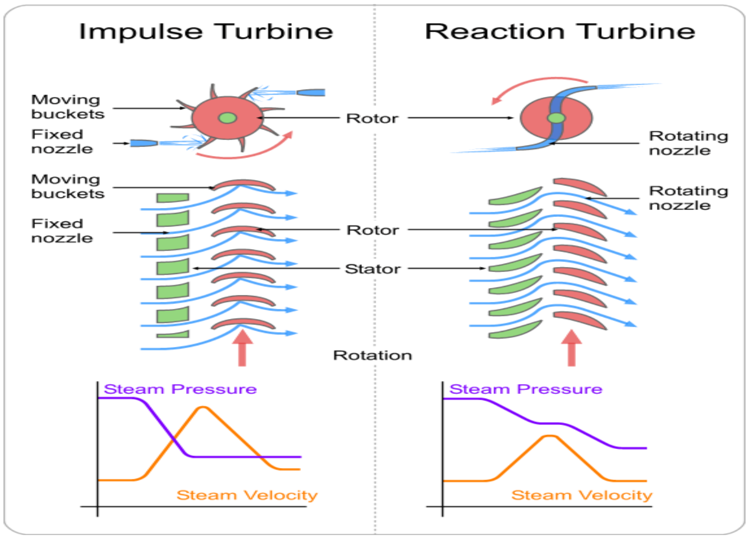
<tr><td>COMPRESSORS</td><td></td><td></td><td></td></tr>
<tr><td>STEAM TURBINES</td><td></td><td colspan="2">
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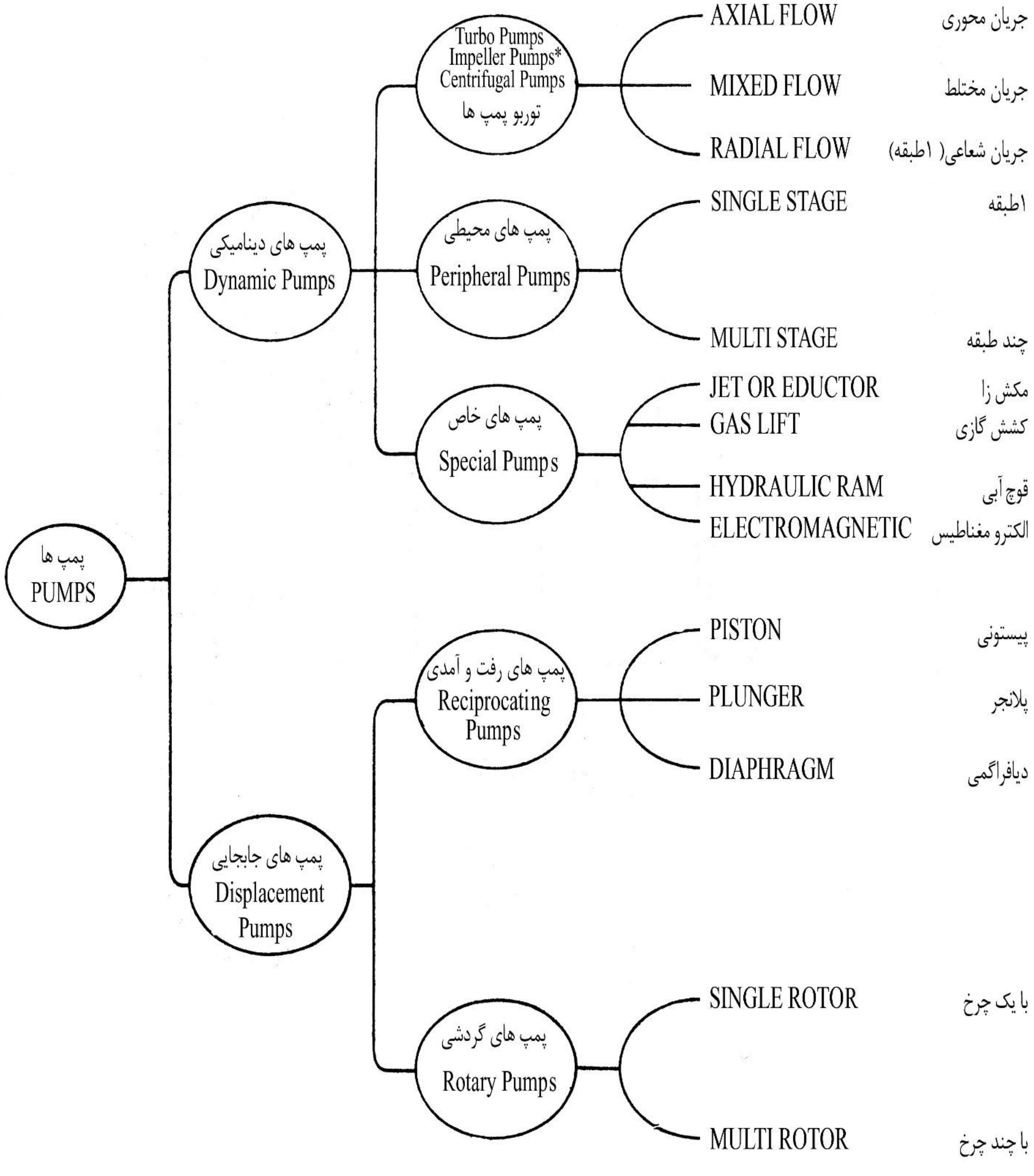
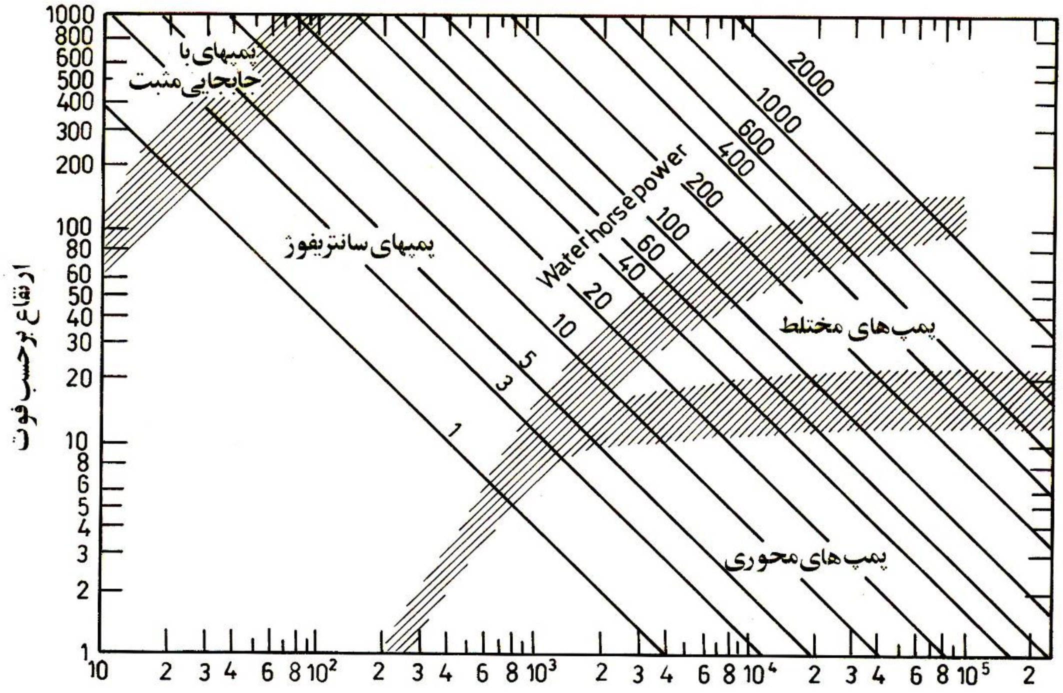
Slide#3- Turbomachinery Course- PUMP CLASSIFICATION

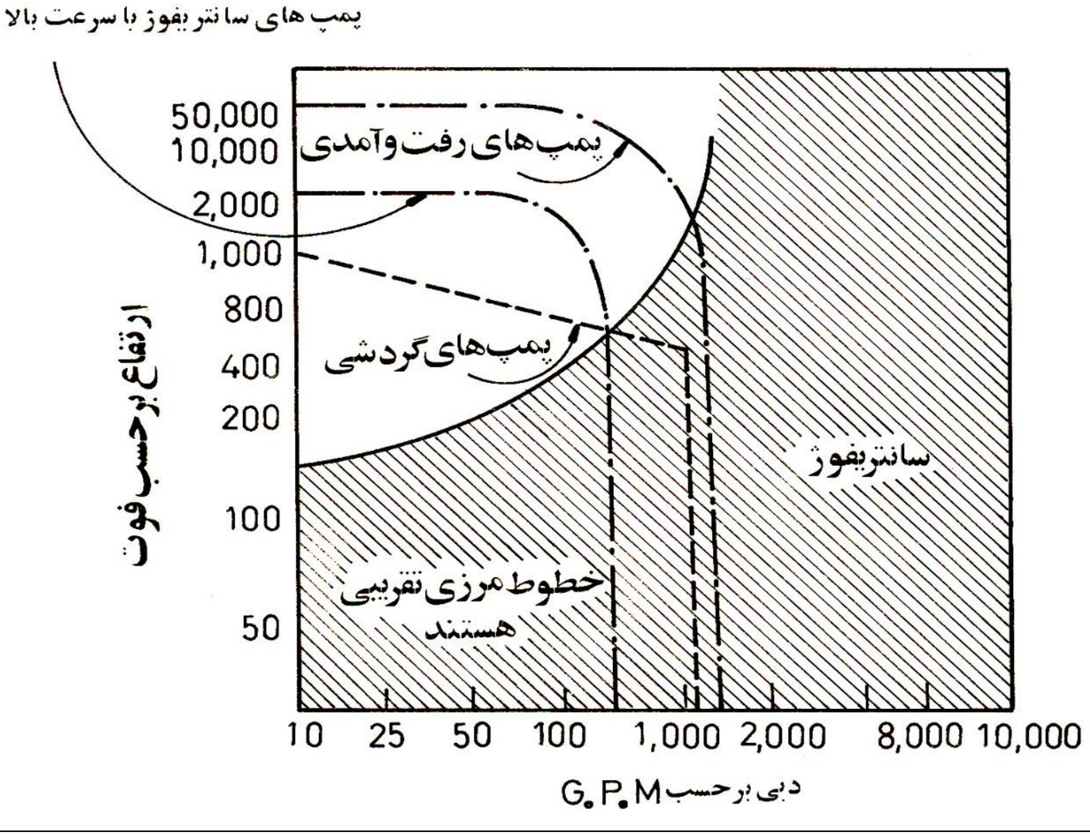


Slide#4- Turbomachinery Course- PUMP CLASSIFICATION

PUMP CLASSIFICATION



G.P.M دبی برحسب



Slide#5- Turbomachinery Course- PUMPS

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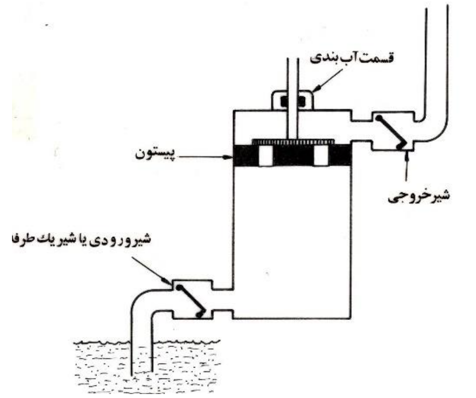
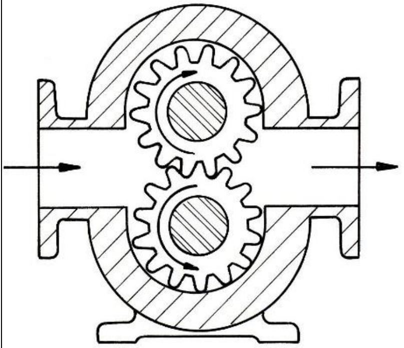
<tr><td rowspan="2">PUMPS</td><td></td><td>
</td><td></td></tr>
<tr><td>TURBO PUMPS</td><td>RECIPROCATING PUMPS</td><td>ROTARY PUMPS</td></tr>
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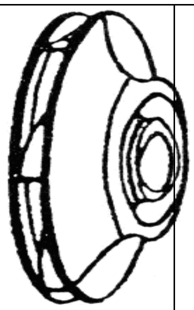
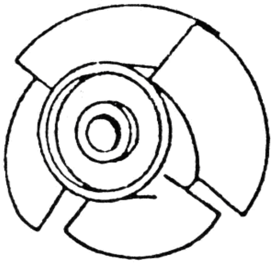
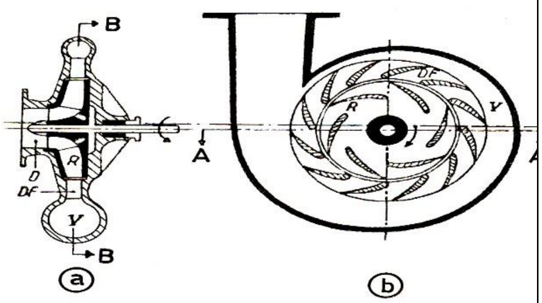
<tr><td rowspan="2">TURBO PUMPS</td><td></td><td></td><td></td><td>
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<tr><td>RADIAL</td><td>MIXED</td><td>AXIAL</td><td>D:DISTRIBUTOR, R:IMPELLER
DF: DIFFUSER, V:VOLUTE</td></tr>
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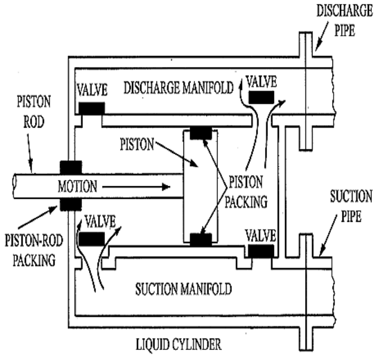
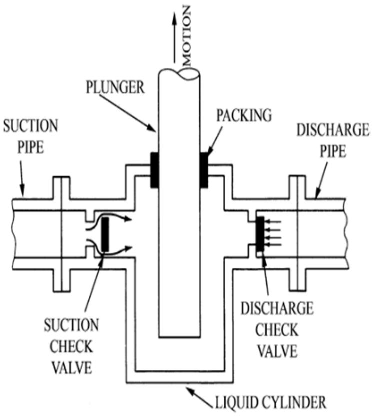
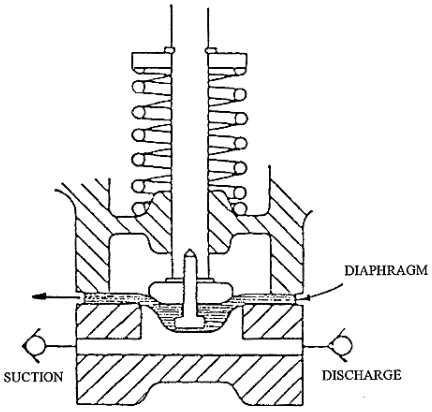
<table>
<tr><td rowspan="2">RECIPROCATING PUMPS</td><td>
</td><td>
</td><td>
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<tr><td>PISTON</td><td>PLUNGER</td><td>DIAPHRAGM</td></tr>
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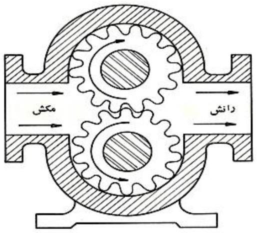
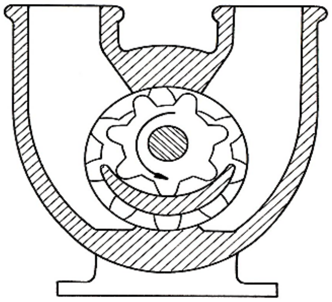
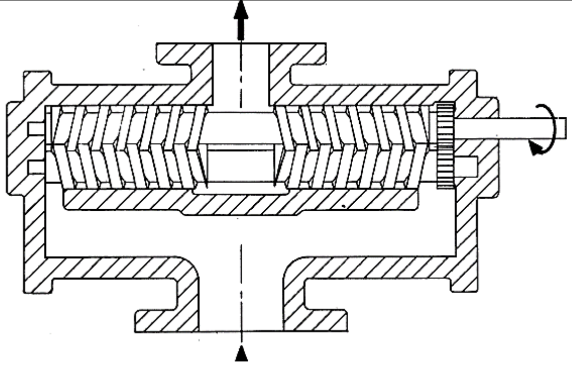
<tr><td rowspan="2">ROTARY PUMPS</td><td>
</td><td></td><td></td></tr>
<tr><td>ROTARY EXTERNAL GEAR</td><td>ROTARY INTERNAL GEAR</td><td>MULTIPLE-SCREW DOUBLE-END ARRANGEMENT</td></tr>
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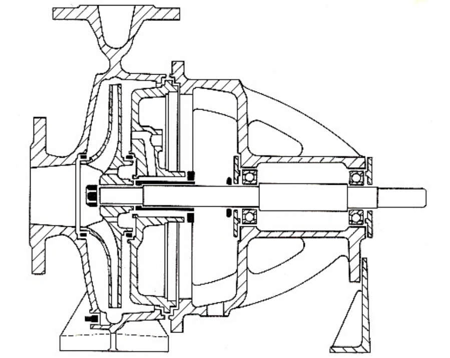
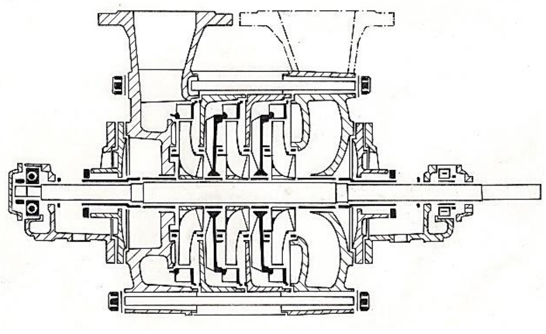
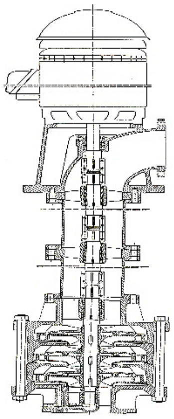
TURBO PUMP CLASSIFICATION



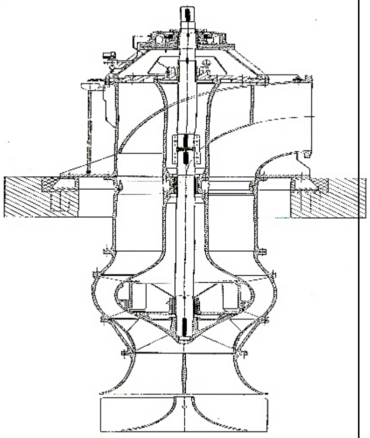
SINGLE-STAGE PUMP



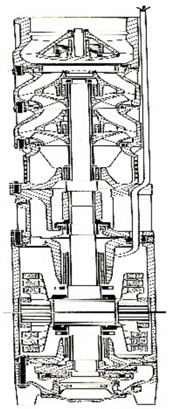
MULTI- STAGE PUMP



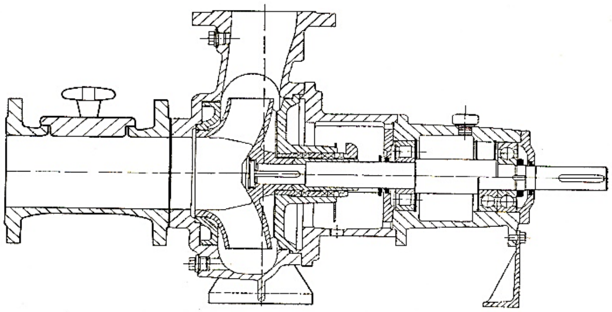
VERTICAL MULTI-STAGE CENTRIFUGAL PUMP



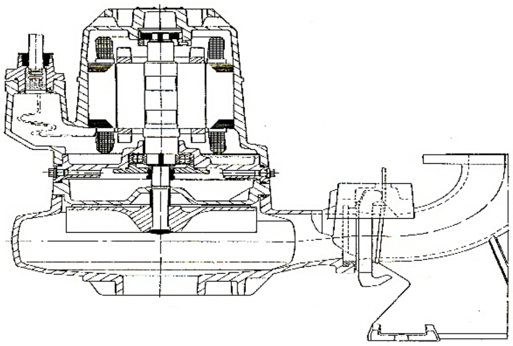
VERTICAL MIXED FLOW SINGLE-STAGE PUMP



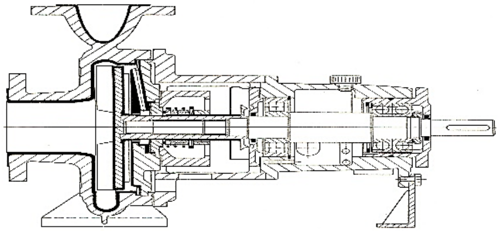
VERTICAL SUBMERSIBLE PUMP



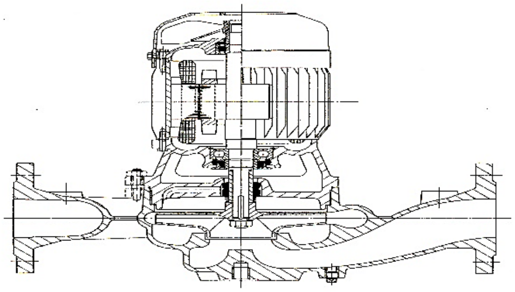
HORIZONTAL SLUDGE PUMP



VERTICAL SUBMERSIBLE SLUDGE PUMP

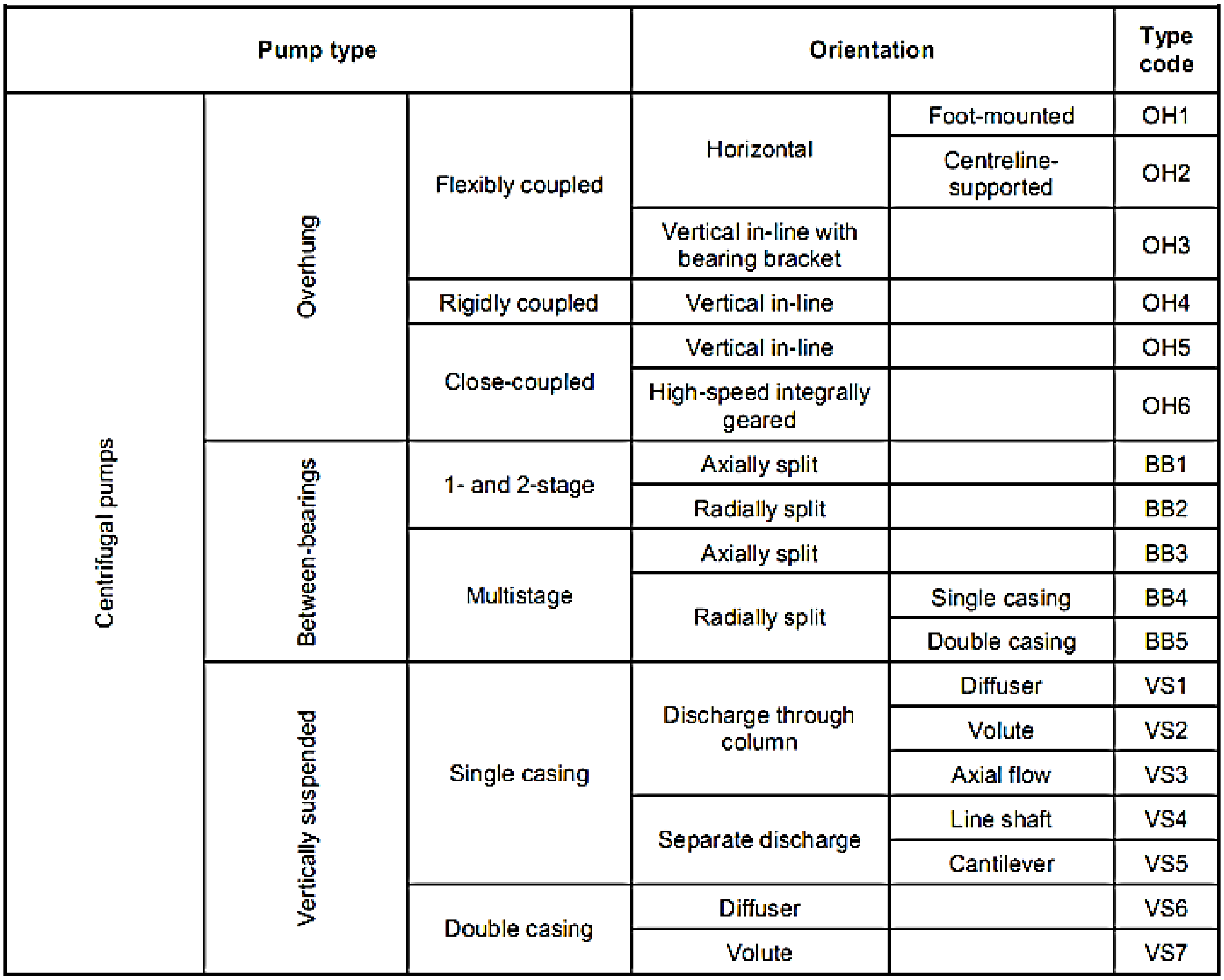


HORIZONTAL CHEMICAL PUMP



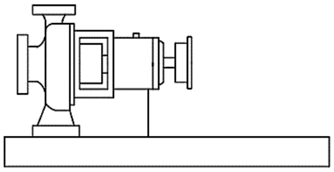
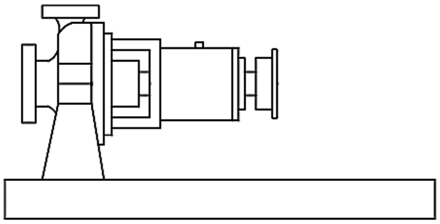
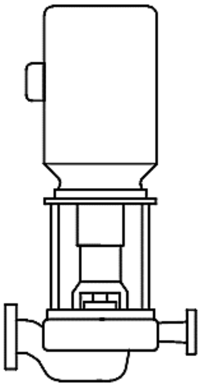
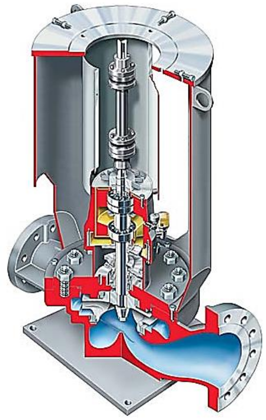
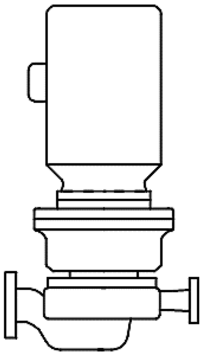
DOUBLE SUCTION PUMP

API 610

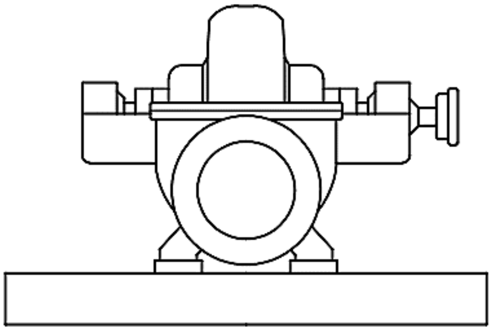
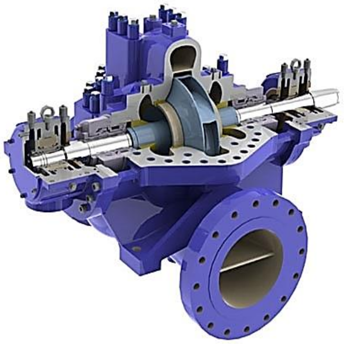
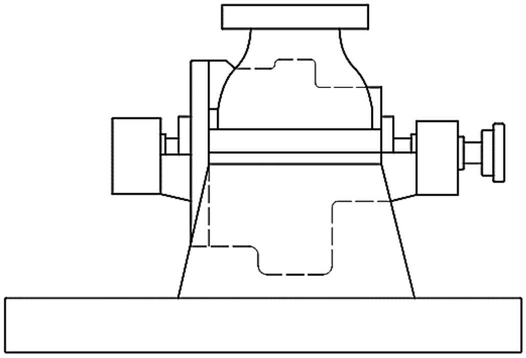
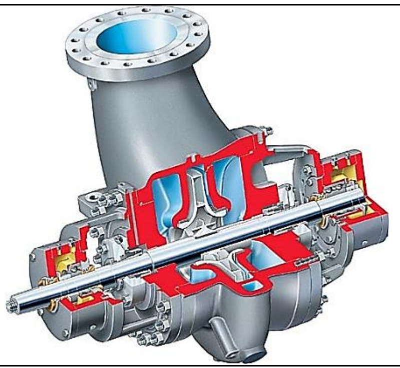
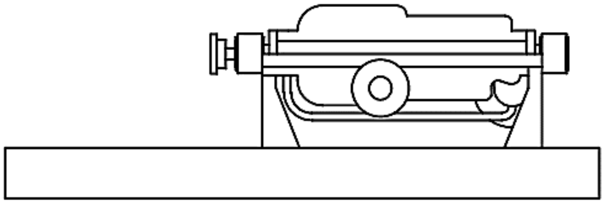
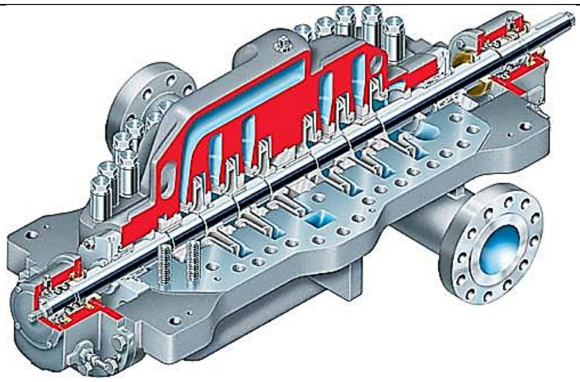
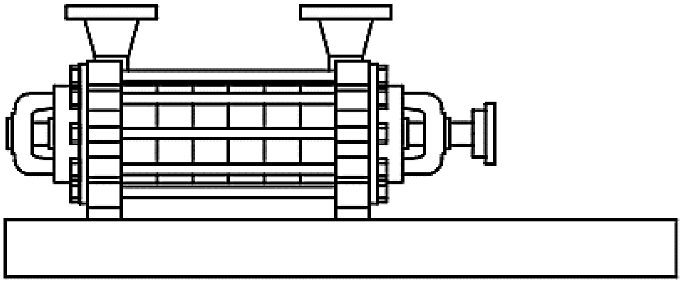
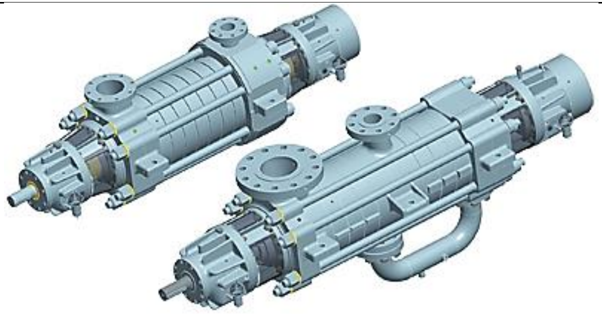


Pump type			Orientation		Type code
Centrifugal pumps	Overhung	Flexibly coupled	Horizontal	Foot-mounted	OH1
				Centreline-supported	OH2
			Vertical in-line with bearing bracket		OH3
		Rigidly coupled	Vertical in-line		OH4
		Close-coupled	Vertical in-line		OH5
			High-speed integrally geared		OH6
	Between-bearings	1- and 2-stage	Axially split		BB1
			Radially split		BB2
		Multistage	Axially split		BB3
			Radially split	Single casing	BB4
				Double casing	BB5
	Vertically suspended	Single casing	Discharge through column	Diffuser	VS1
				Volute	VS2
				Axial flow	VS3
			Separate discharge	Line shaft	VS4
				Cantilever	VS5
		Double casing	Diffuser		VS6
			Volute		VS7

API 610

OH1		
	FOOT-MOUNTED SINGLE-STAGE OVERHUNG PUMPS SHALL BE DESIGNATED PUMP TYPE OH1	
OH2		
	CENTRELINE-MOUNTED SINGLE-STAGE OVERHUNG PUMPS. THE PUMPS ARE MOUNTED ON A BASEPLATE AND ARE FLEXIBLY COUPLED TO THEIR DRIVERS.	
OH3		
	VERTICAL IN-LINE SINGLE-STAGE OVERHUNG PUMPS WITH SEPARATE BEARING BRACKETS. THE PUMPS AND THEIR DRIVERS ARE FLEXIBLY COUPLED	
OH6		
	HIGH-SPEED INTEGRAL GEAR-DRIVEN SINGLE-STAGE OVERHUNG PUMPS	

API 610

BB1		
	AXIALLY SPLIT ONE- AND TWO-STAGE BETWEEN-BEARINGS PUMPS	
BB2		
	RADIALLY SPLIT ONE- AND TWO-STAGE BETWEEN-BEARINGS PUMPS	
BB3		
	AXIALLY SPLIT MULTISTAGE BETWEEN-BEARINGS PUMPS	
BB4		
	SINGLE-CASING RADIALLY SPLIT MULTISTAGE BETWEEN-BEARINGS PUMPS	

API 610

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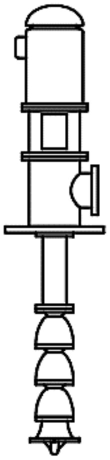
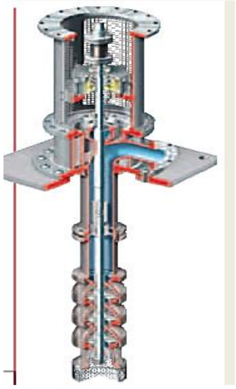
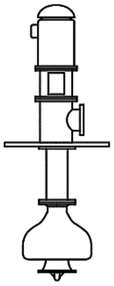
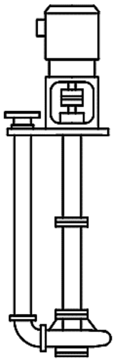
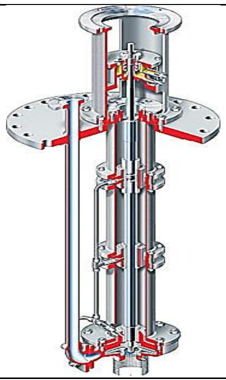
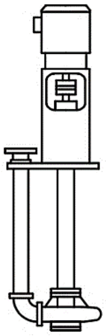
<tr><td rowspan="2">VS1</td><td></td><td></td></tr>
<tr><td colspan="2">WET PIT, VERTICALLY SUSPENDED, SINGLE-CASING DIFFUSER PUMPS WITH DISCHARGE THROUGH THE COLUMN</td></tr>
<tr><td rowspan="2">VS2</td><td></td><td></td></tr>
<tr><td colspan="2">WET PIT, VERTICALLY SUSPENDED SINGLE-CASING VOLUTE PUMPS WITH DISCHARGE THROUGH THE COLUMN</td></tr>
<tr><td rowspan="2">VS4</td><td></td><td></td></tr>
<tr><td colspan="2">VERTICALLY SUSPENDED, SINGLE-CASING VOLUTE LINE-SHAFT DRIVEN SUMP PUMPS</td></tr>
<tr><td rowspan="2">VS5</td><td></td><td></td></tr>
<tr><td colspan="2">VERTICALLY SUSPENDED CANTILEVER SUMP PUMPS</td></tr>
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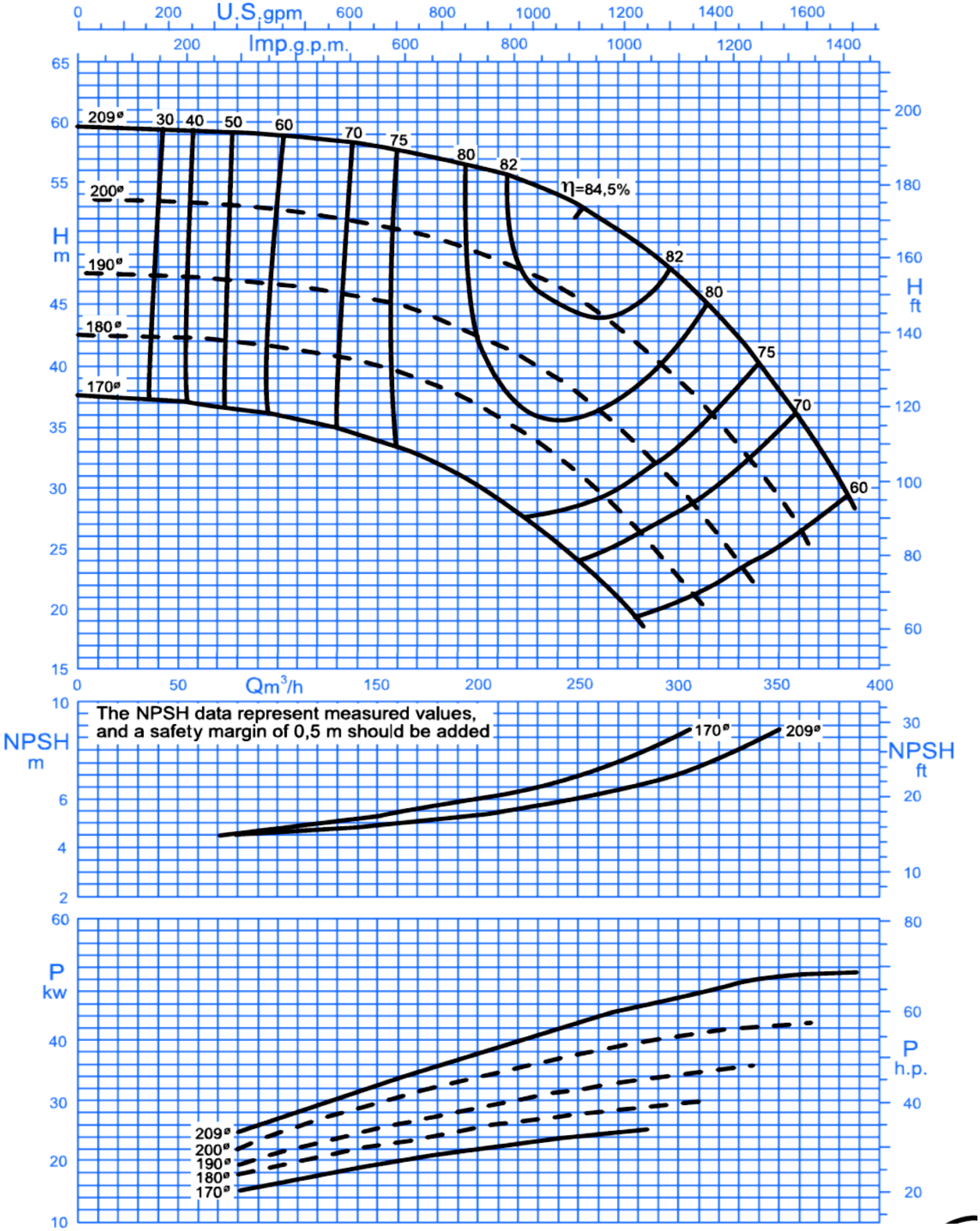
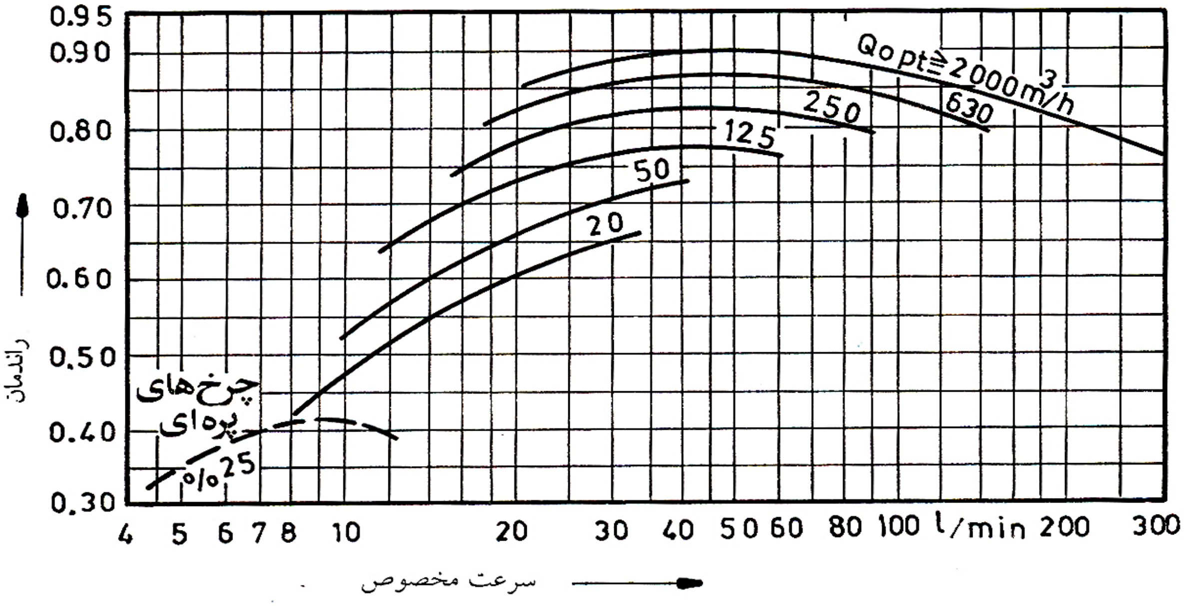
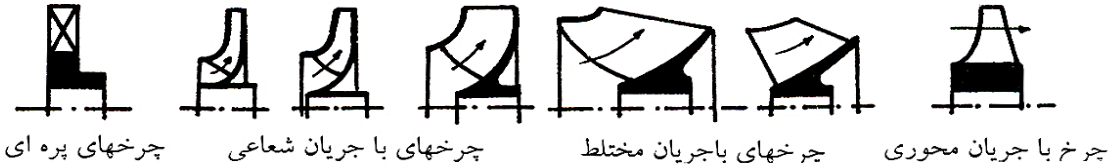
Slide#11- Turbomachinery Course- PUMP CHARACTERISTICS (100-200)



2900 rpm / ۲۹۰۰ دور موتور





- سرعت مخصوص عبارتست از:

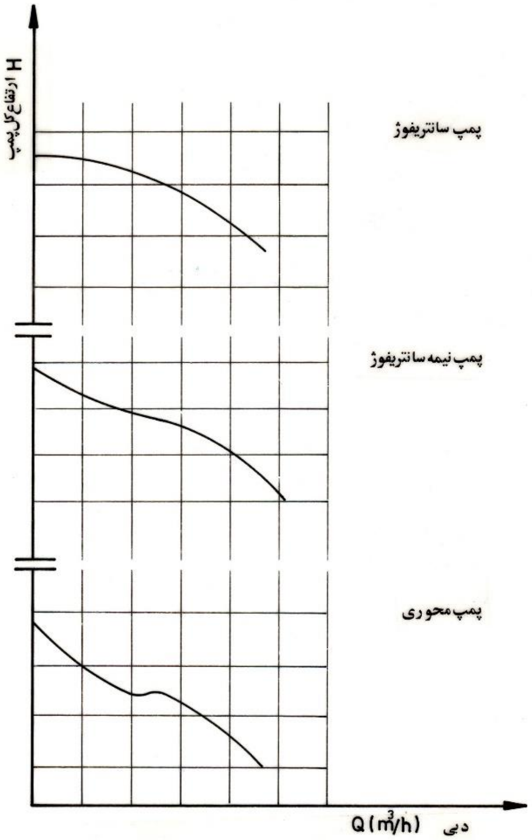
$$N_s = N\frac{Q^{1/2}}{H^{3/4}}$$

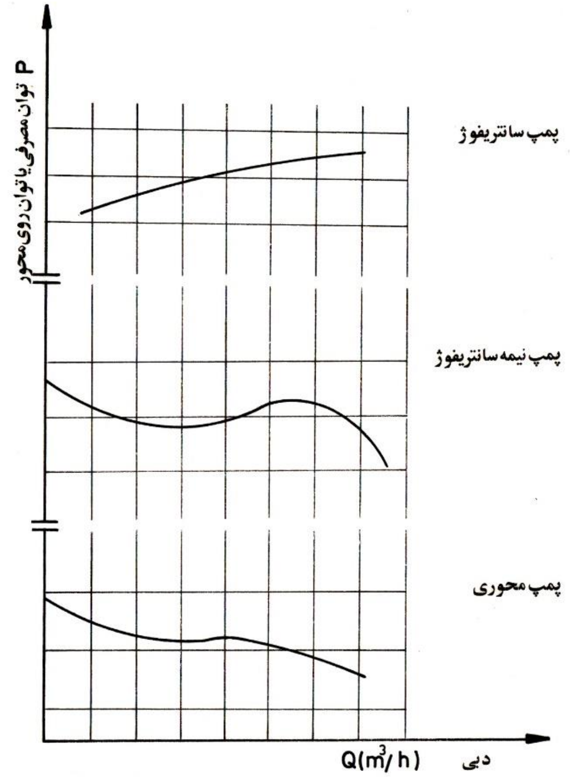
در این رابطه :

Q: دبی در نقطهٔ راندمان ماکزیمم برحسب مترمکعب بر ثانیه (m^3/s)

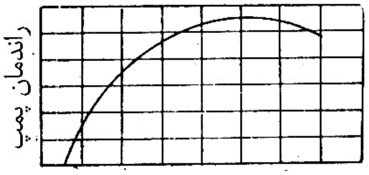
H : ارتفاع در نقطهٔ راندمان ماکزیمم برحسب متر(m)

N : سرعت دورانی پمپ برحسب 1 / min

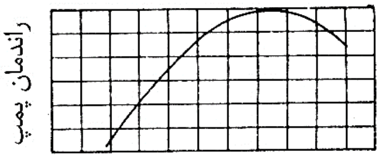


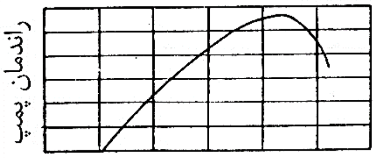


پمپ سانتریفوژ

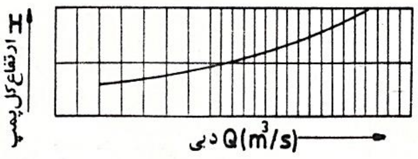


پمپ نیمه سانتریفوژ

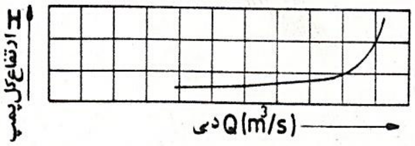




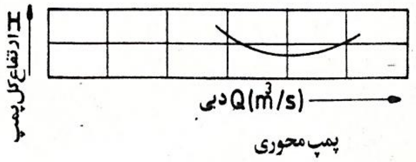
پمپ محوری



پمپ سانتریفوژ

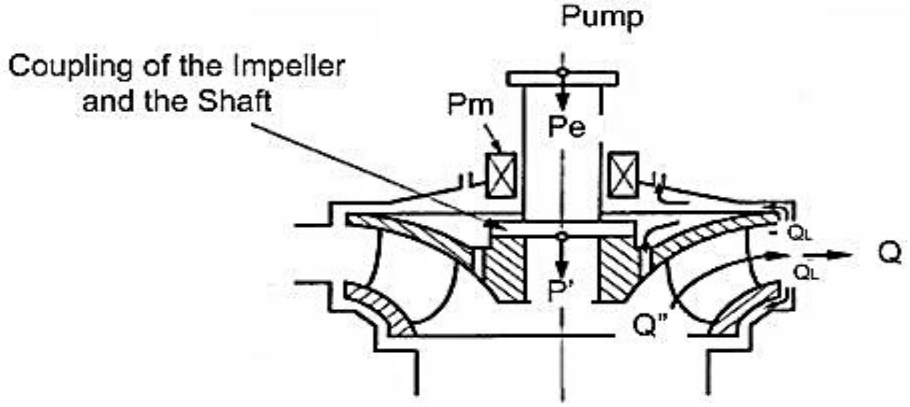


پمپ نیمه سانتریفوژ



پمپ محوری

Slide#14- Turbomachinery Course- PUMP-LOSSES



$$Q = Q" - Q_L$$

$$P = E.(\rho Q)$$

$$P_s = P' + P_m$$

$$P' = P" + P_D$$

$$\eta_V = \frac{Q}{Q"} = \frac{Q}{Q + Q_L}$$

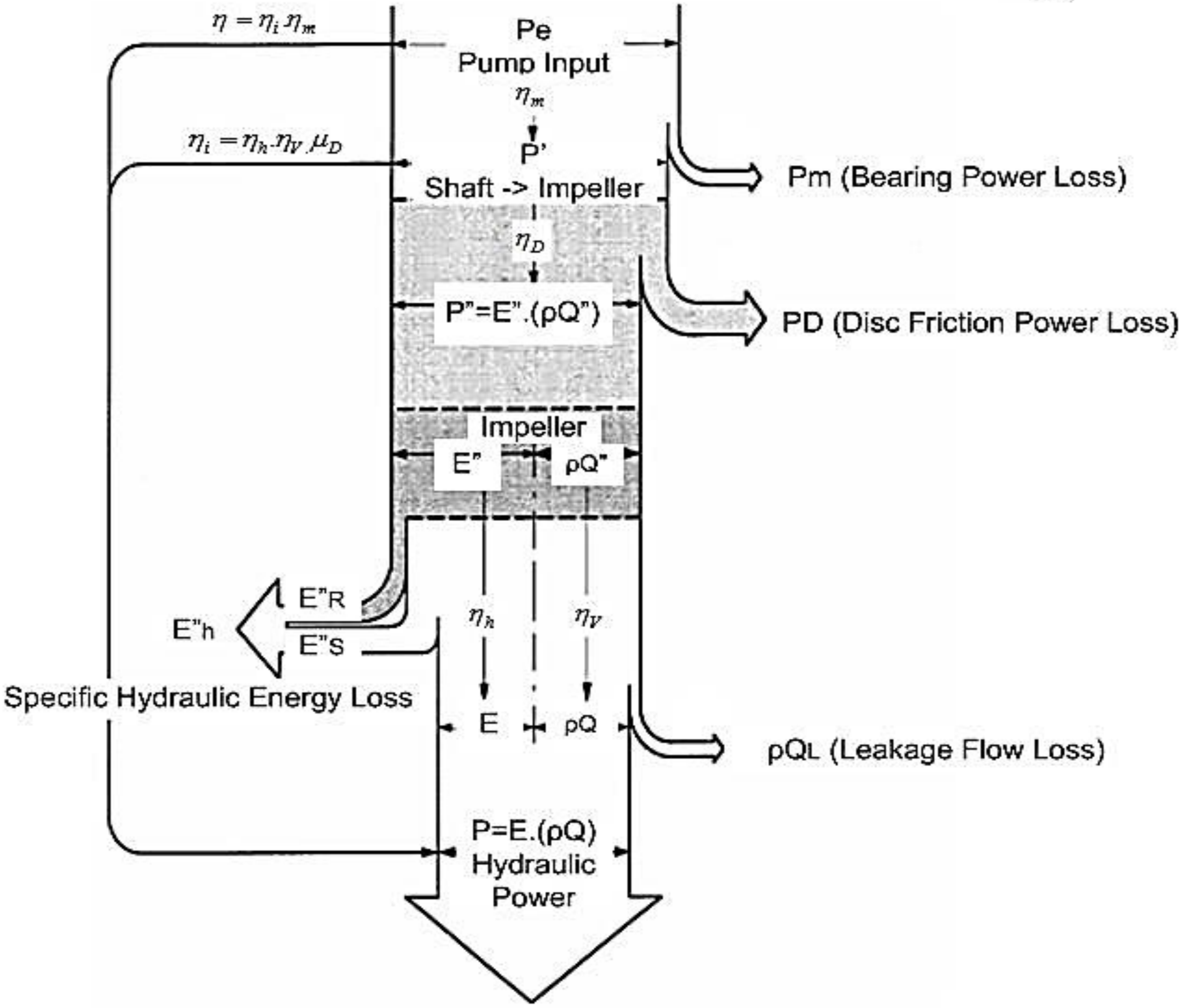
$$\eta_h = \frac{E}{E"}$$

$$\eta_D = \frac{P"}{P'} = \frac{P"}{P" + P_D}$$

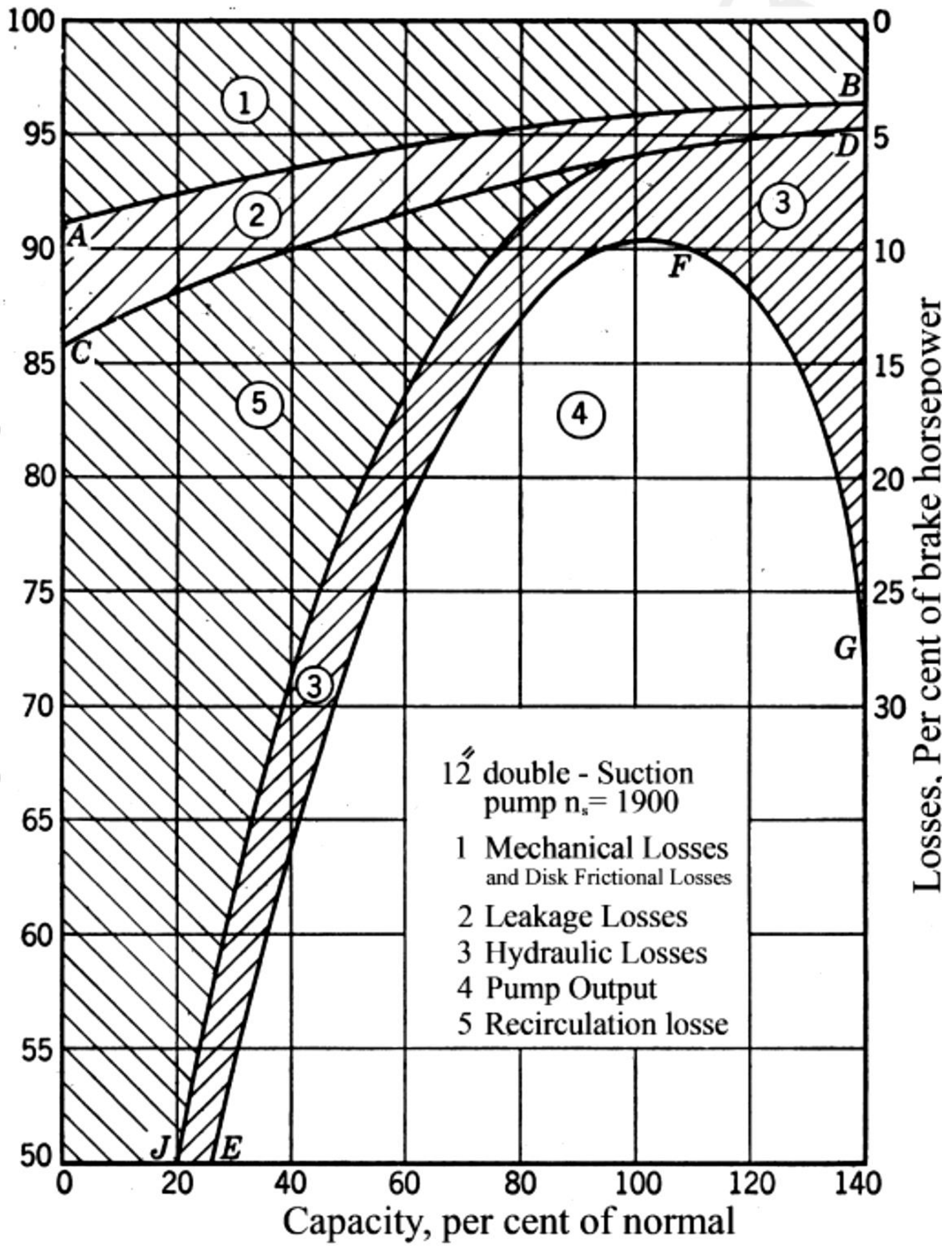
$$\eta_m = \frac{P'}{P_s} = \frac{P'}{P' + P_m}$$

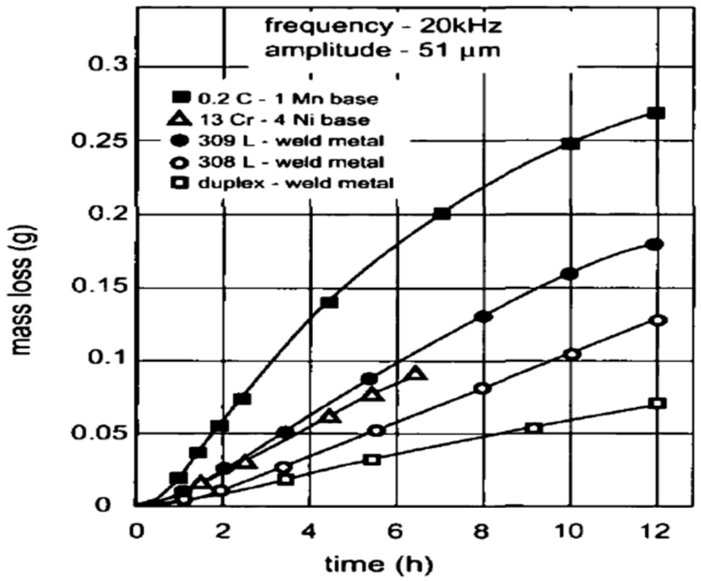
$$\eta_{\ i} = \eta_h . \eta_V . \eta_D = \frac{P}{P'}$$

$$\eta = \eta_i . \eta_m = \frac{P}{P_s}$$

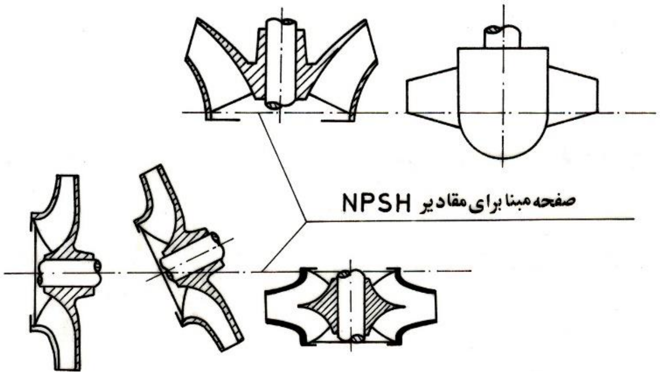


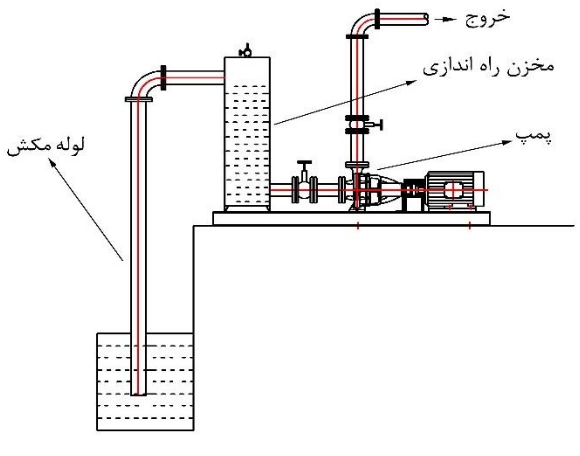
Slide#15- Turbomachinery Course- PUMP-LOSSES

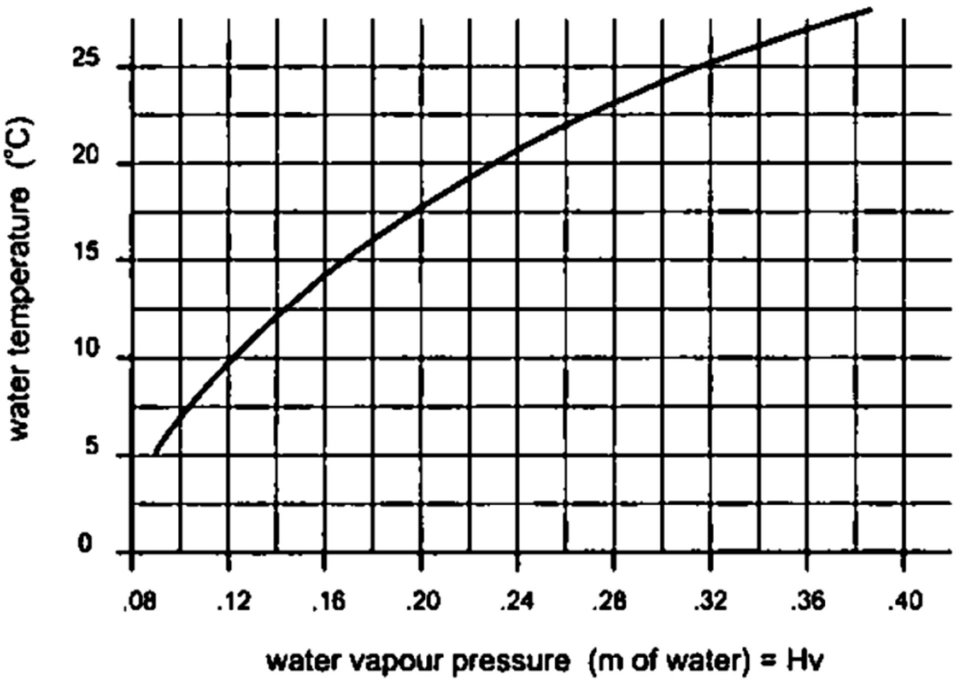


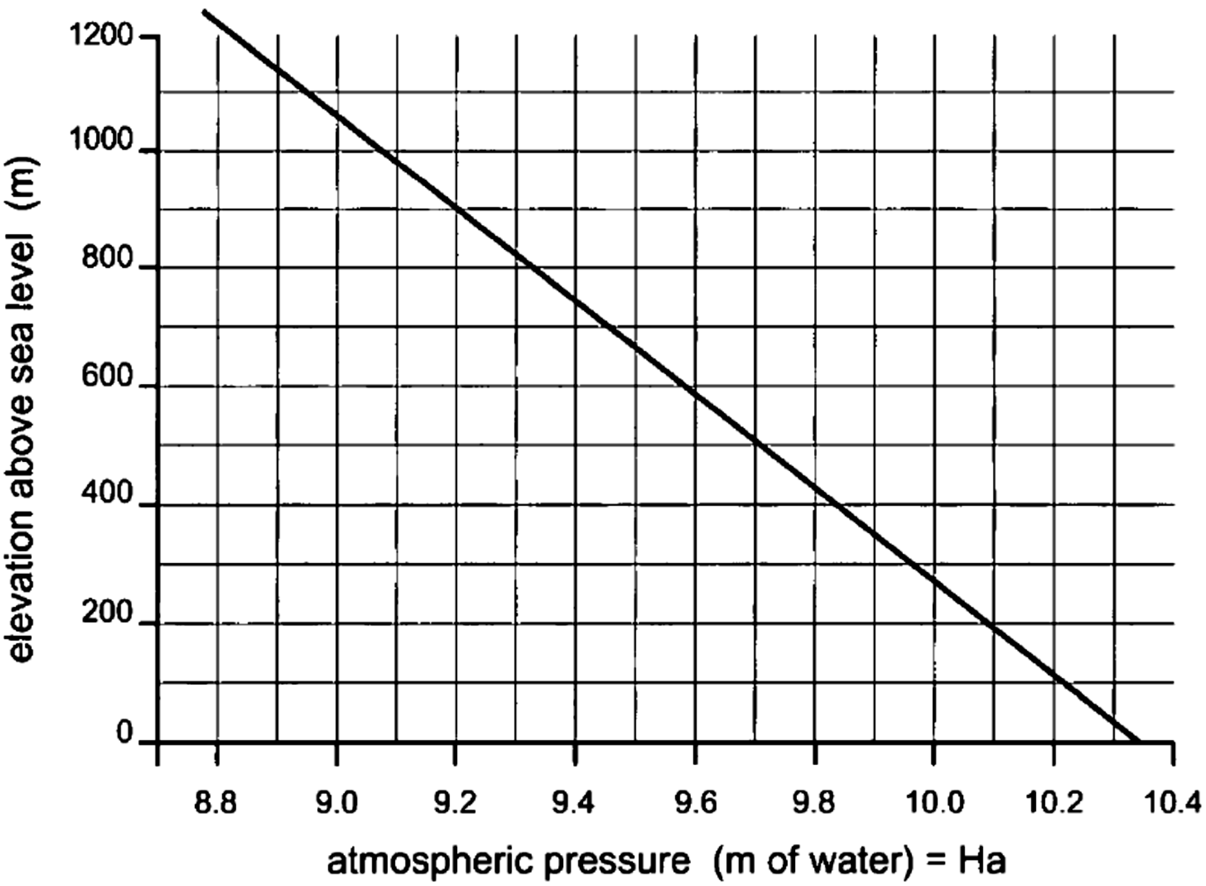


material	cavitation rate (mg/h)
A-27 – cast	35.0
CA6NM – cast	15.0
308 Stainless Steel – welded	15.0
301 Stainless Steel – welded	6.0
Stellite® 21 – welded	1.4
Stellite® 6 – welded	0.7

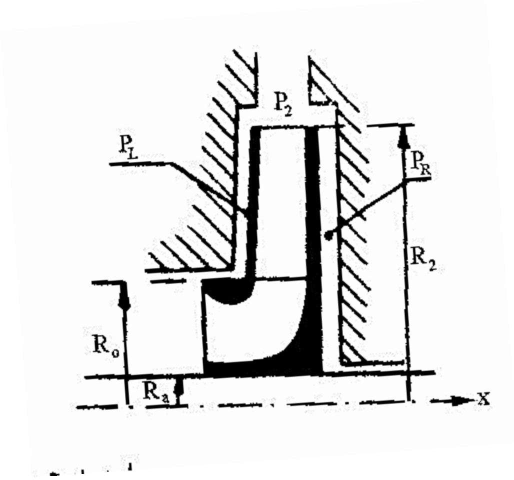




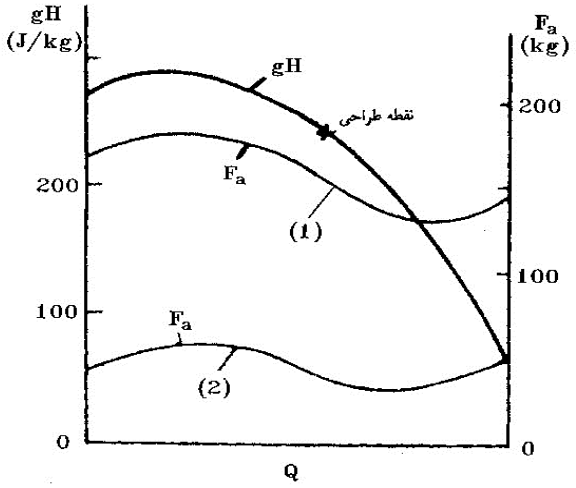

water temperature (°C)
25
20
15
10
5
0
.08
.12
.16
.20
.24
.28
.32
.36
.40
water vapour pressure (m of water) = Hv

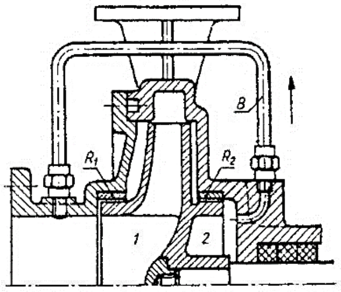

elevation above sea level (m)
1200
1000
800
600
400
200
0
8.8
9.0
9.2
9.4
9.6
9.8
10.0
10.2
10.4
atmospheric pressure (m of water) = Ha

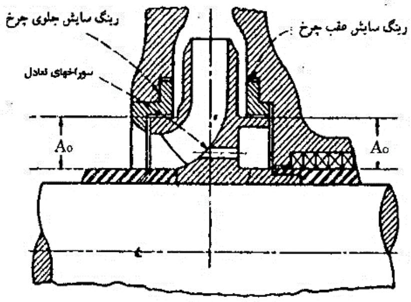
Slide#18- Turbomachinery Course- PUMP-AXIAL & RADIAL FORCES



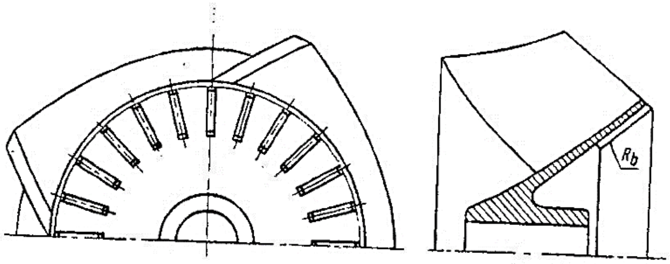
- نیروهای محوری وارد بر چرخ

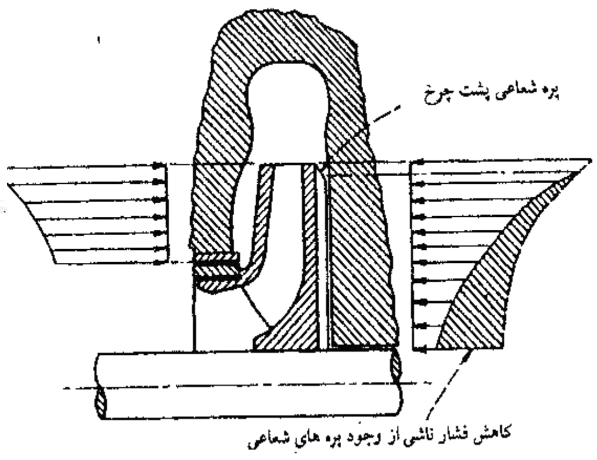






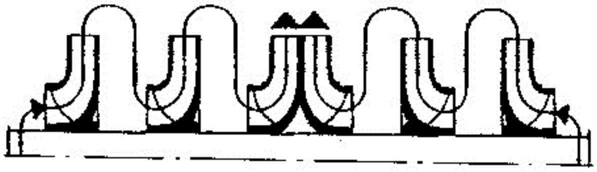
- کاهش نیروهای محوری وارد بر چرخ از طریق اتاق تعادلی با ایجاد سوراخ در چرخ و لوله رابط



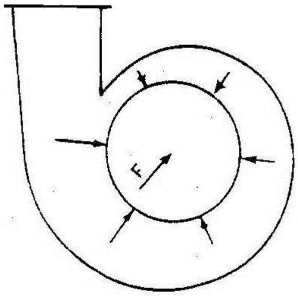


- کاهش نیروهای محوری وارد بر چرخ از طریق پره های شعاعی در پشت چرخ

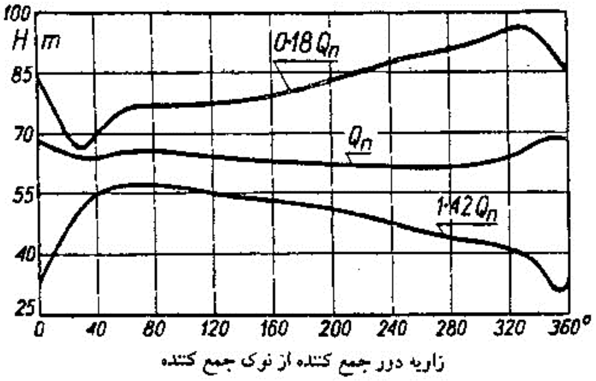
Slide#19- Turbomachinery Course- PUMP-AXIAL & RADIAL FORCES



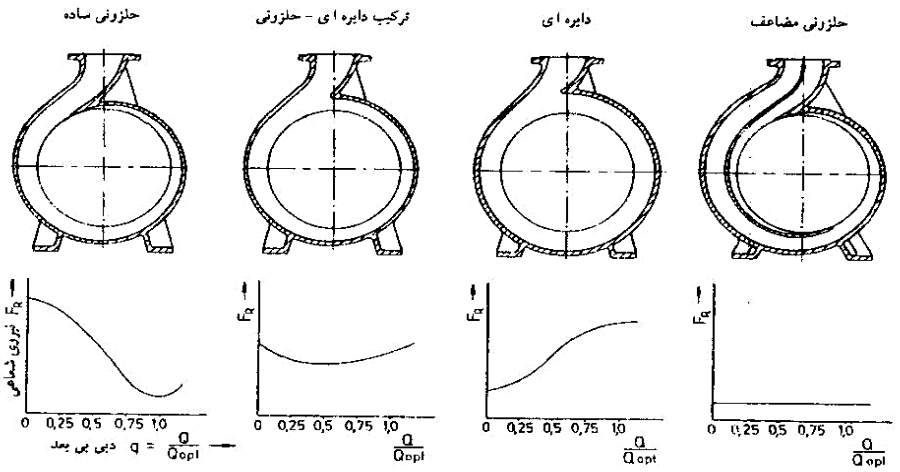
- کاهش نیروهای محوری وارد بر پمپ چند طبقه از طریق چیدمان چرخ ها



- نیروی شعاعی وارد بر چرخ

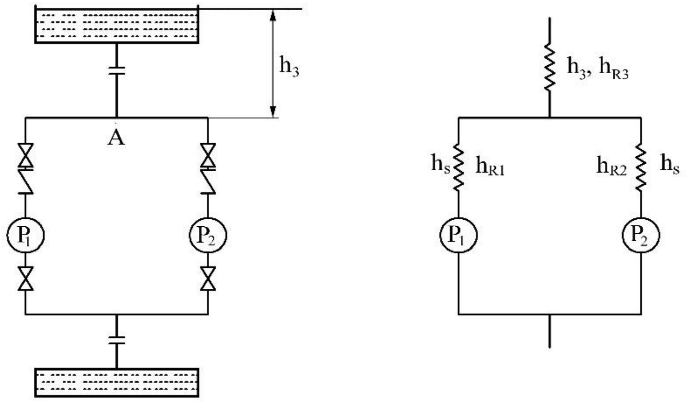


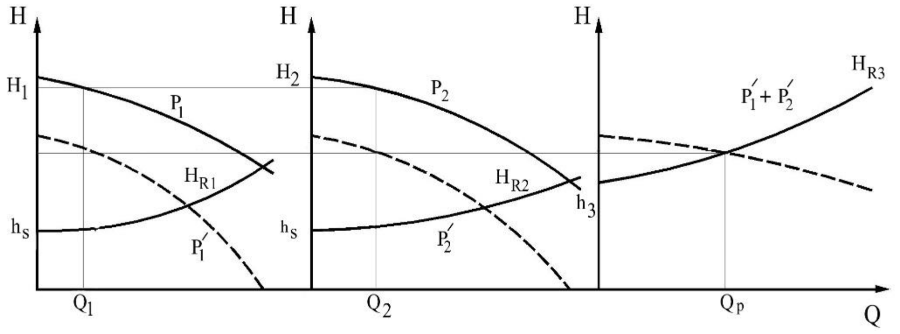
- تغییرات فشار استاتیک پیرامون چرخ



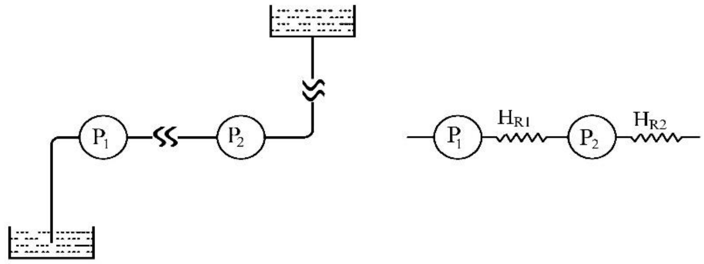
- تاثیر شکل حلزونی بر نیروی شعاعی

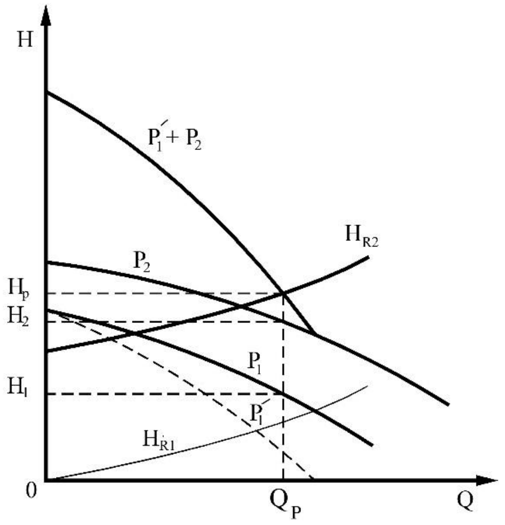
دو پمپ موازی در مداری با افت فشار:



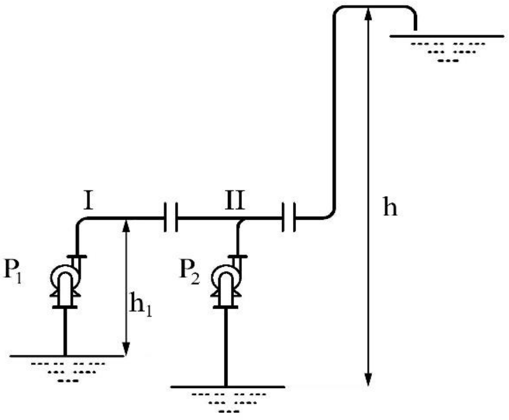


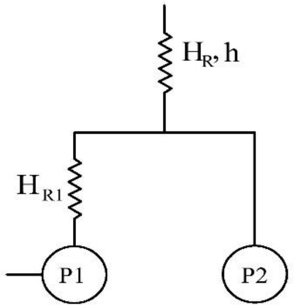
کارکرد دو پمپ بطور سری، هنگامیکه بین آنها مقاومت وجود داشته باشد:

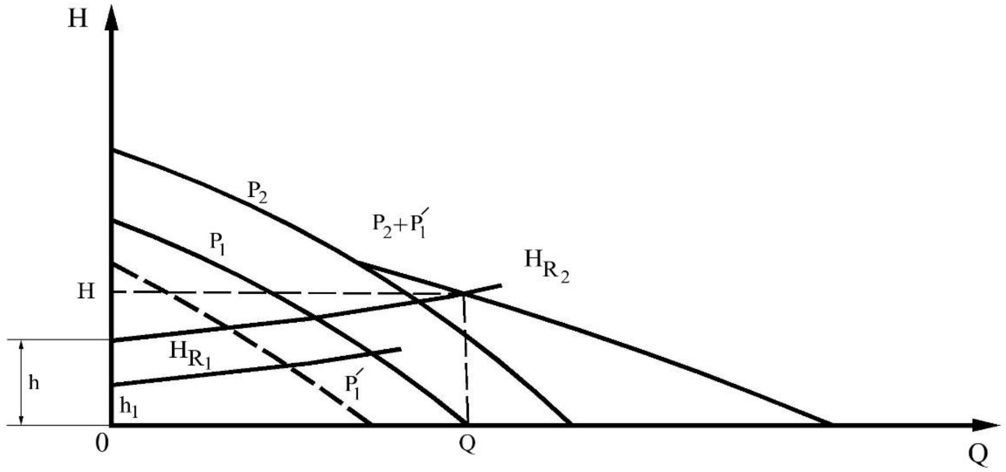


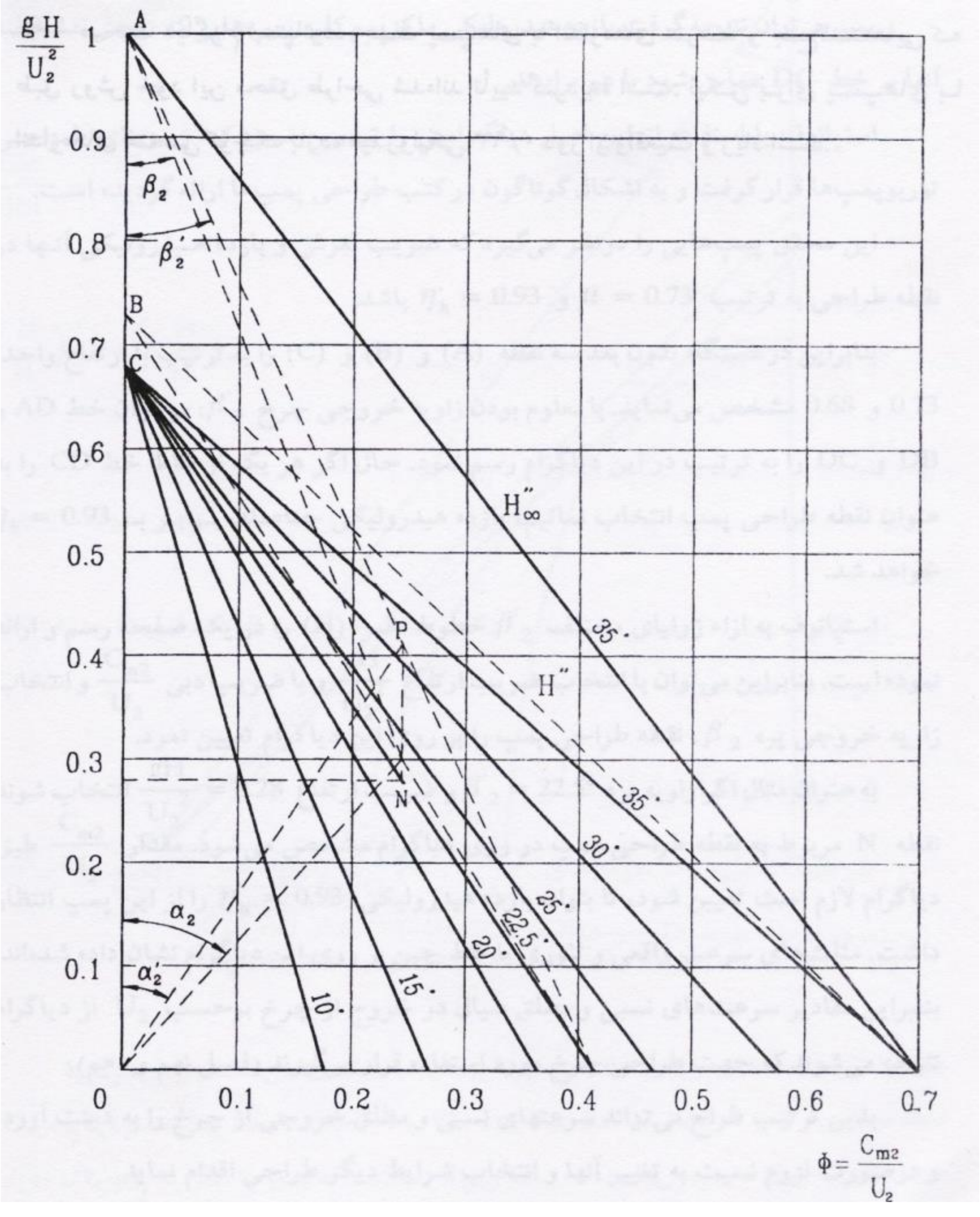


- **کار دو پمپ به صورت موازی، هنگامی که در فاصله دور از یکدیگر قرار گرفته باشند:**





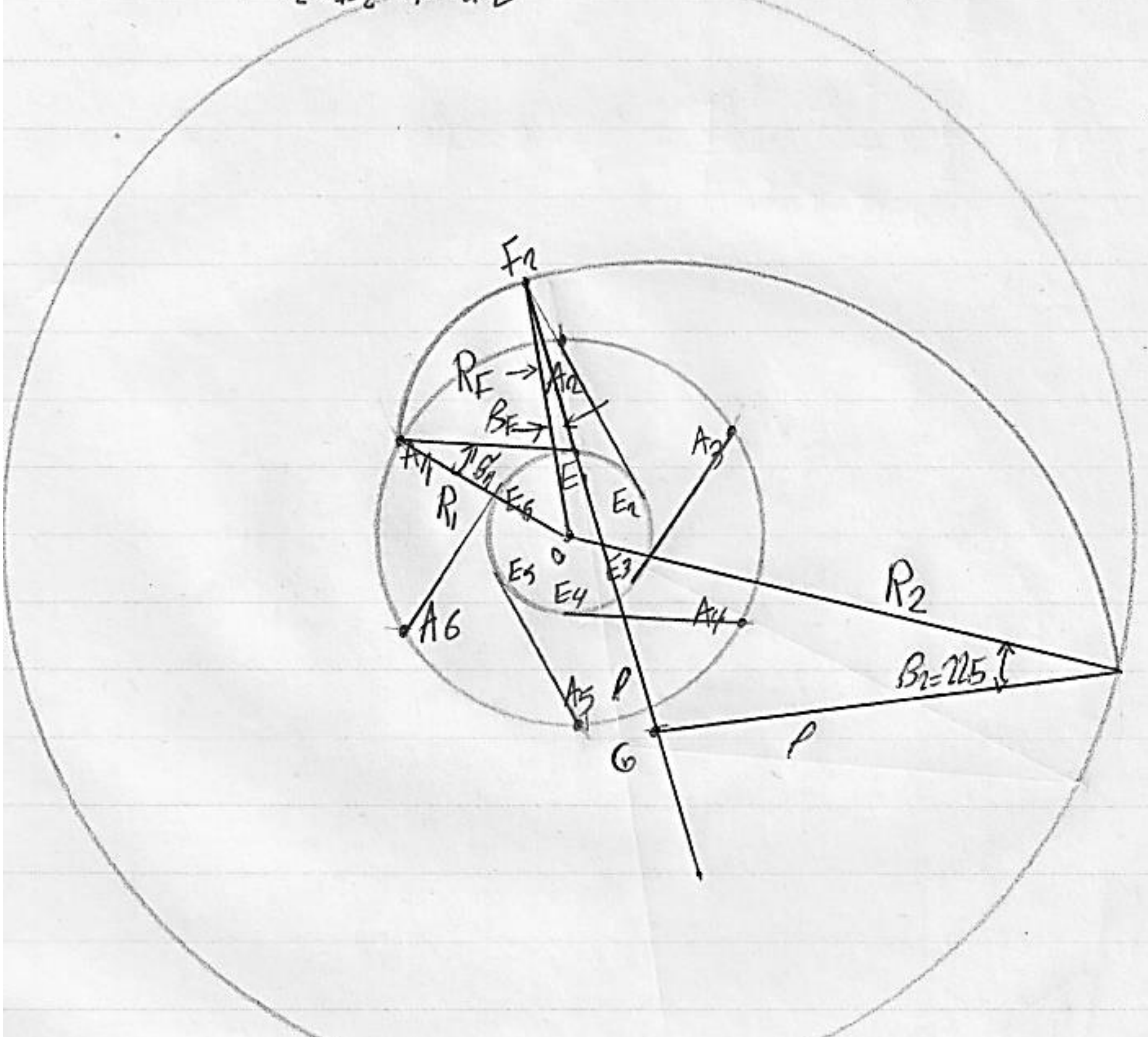



$\frac{gH}{U_2^2}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
A
B
C
P
N
β_2
β_2'
α_2
α_2'
H''_∞
H''
35
35
30
25
22.5
20
15
10
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\Phi = \frac{C_{m2}}{U_2}$

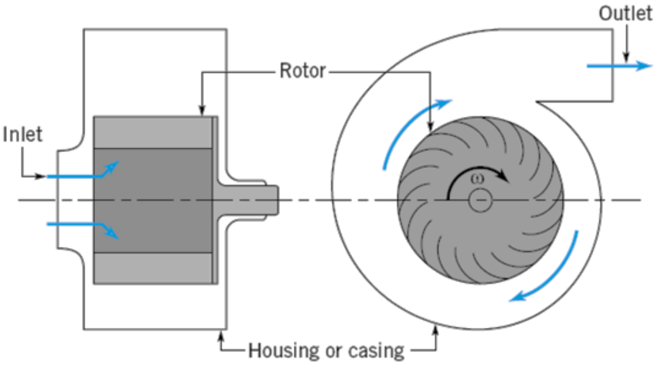
$\beta'_1 = 24\,mm,\ \beta'_2 = 22.5\,mm,\ R_1 = 31\,mm,\ R_2 = 92\,m$

$\delta = D_1 \sin\beta'_1 \qquad \frac{\delta}{2} = 31 \sin 24 = 12.6\ mm$

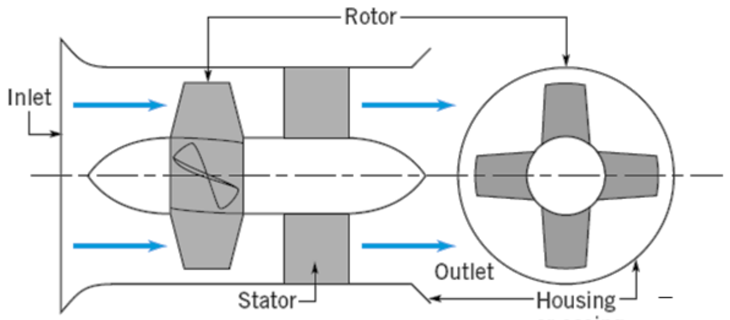
$$\rho = \frac{1}{2}\,\frac{R_2^2 - R_E^2}{R_2 \cos\beta'_2 - R_E \cos\beta'_E} = \frac{1}{2} \times \frac{92^2 - 40^2}{92 \cos 22.5 - 40 \cos 5} = 76\,mm$$



انواع فن:

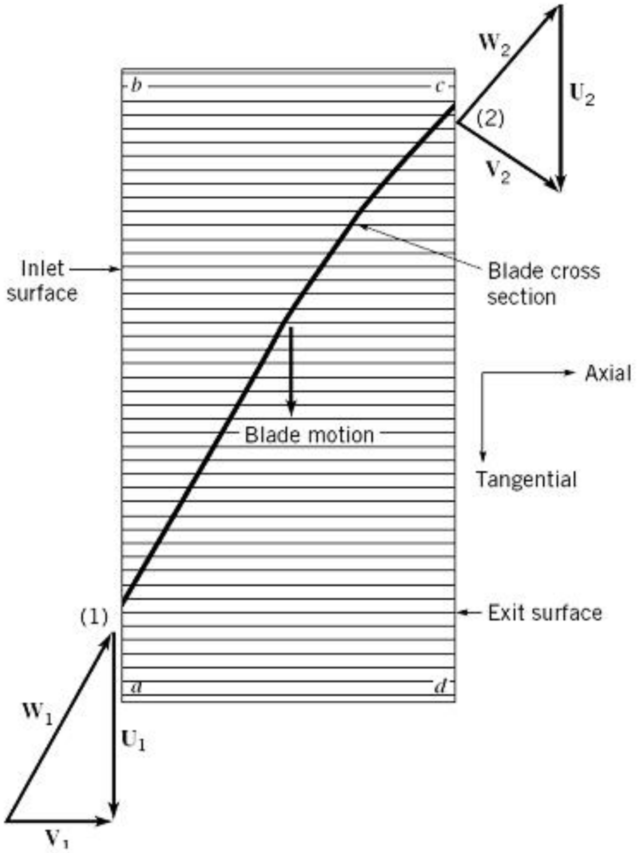


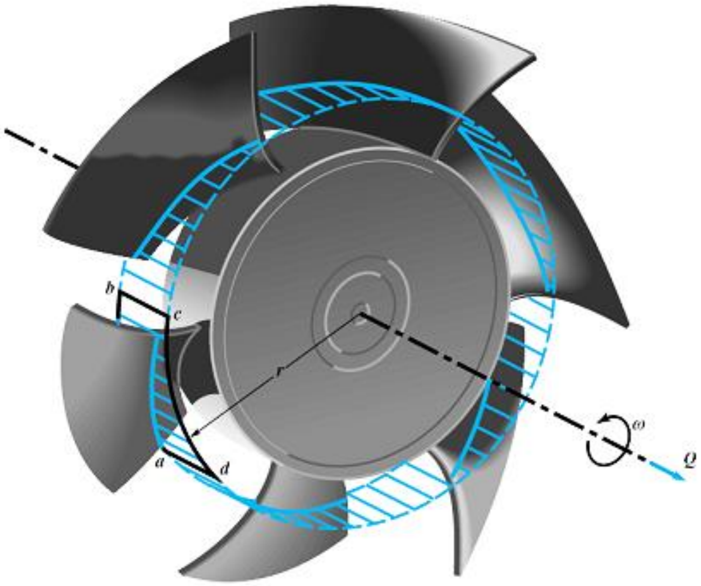
(*a*) Radial flow fan



(*b*) Axial-flow fan

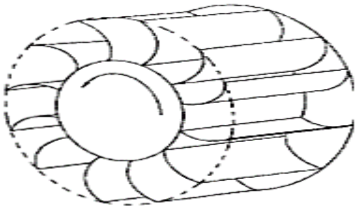
پروفیل سرعت در یک فن محوری:

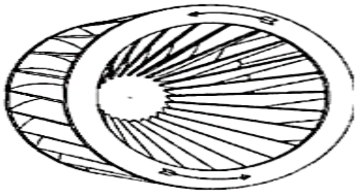


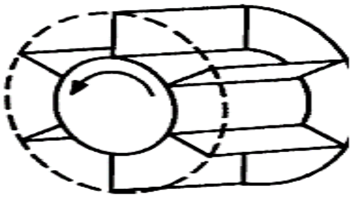


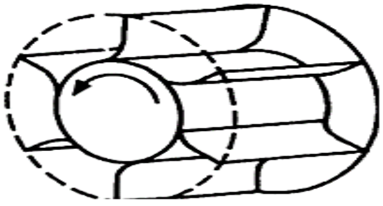
فن‌های سانتریفوژ:

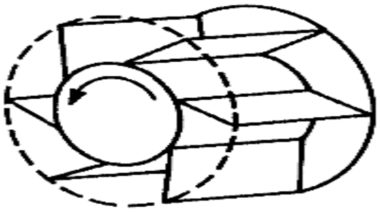
(۱)پروانه با پره‌های با انحنائ رو به جلو (الف)، (۲)پروانه با پره‌های با انحنائ رو به جلوی عمیق (ب)، (۳) پره‌های شعاعی (ج)، (۴) پره‌های با نوک شعاعی (د)، (۵) پره‌های صاف رو به عقب (ه)، (۶) پره‌های با انحناء رو به عقب (و)، (۷) پره‌های با انحناء معکوس که این پره‌ها دارای انحناء رو به عقب در محل نوک پره و انحناء رو به جلو در محل هاب (ز)، (۸) پره‌های ایرفویل رو به عقب (ر)

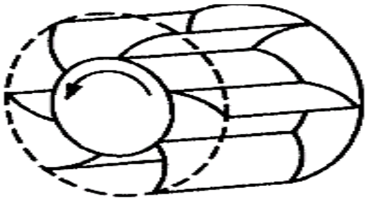

(الف)

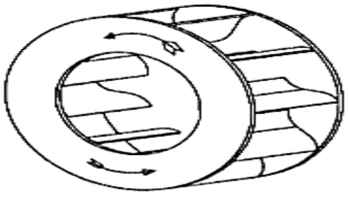

(ب)

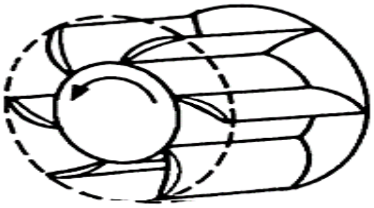

(ج)


(د)


(ه)

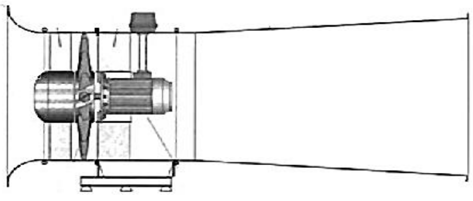

(و)

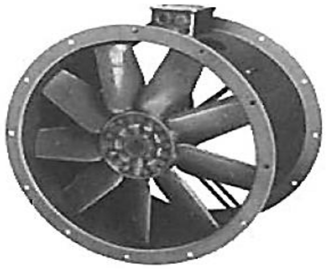

(ز)

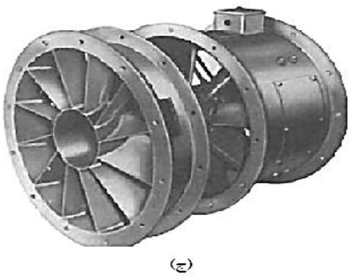

(ر)

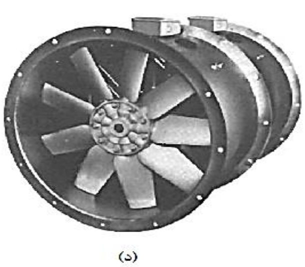
فن‌های محوری:

(۱) فن‌های محوری کانالی (Ducted Axial Fans) (الف)، (۲)- فن‌های محوری لوله‌ای (Tube Axial Fans) که از دو قسمت اصلی پروانه و محفظه تشکیل شده‌اند و حاوی پره‌های هادی نمی باشند شکل (ب) (۳)- فن‌های محوری با پره‌های هادی (Vane Axial Fan) که پره‌های هادی در پایین دست ، بالا دست و یا هردو نصب می‌شوند. پره‌های هادی جهت استحصال انرژی چرخشی سیال و افزایش راندمان فن نصب می‌شوند شکل (ج) (۴)- فن‌های محوری با دو پروانه و جهت چرخش متفاوت، این نوع از فن‌های محوری از دو پروانه مجزا که همواره با دو موتور در جهت‌های مختلف دوران می‌کنند، تشکیل شده‌اند. بدین وسیله جریان چرخشی تولید شده توسط پروانه اول، بوسیله پروانه دوم از بین می‌رود. همچنین انرژی جریان چرخشی استحصال و به فشار استاتیک تبدیل می‌شود شکل (د)

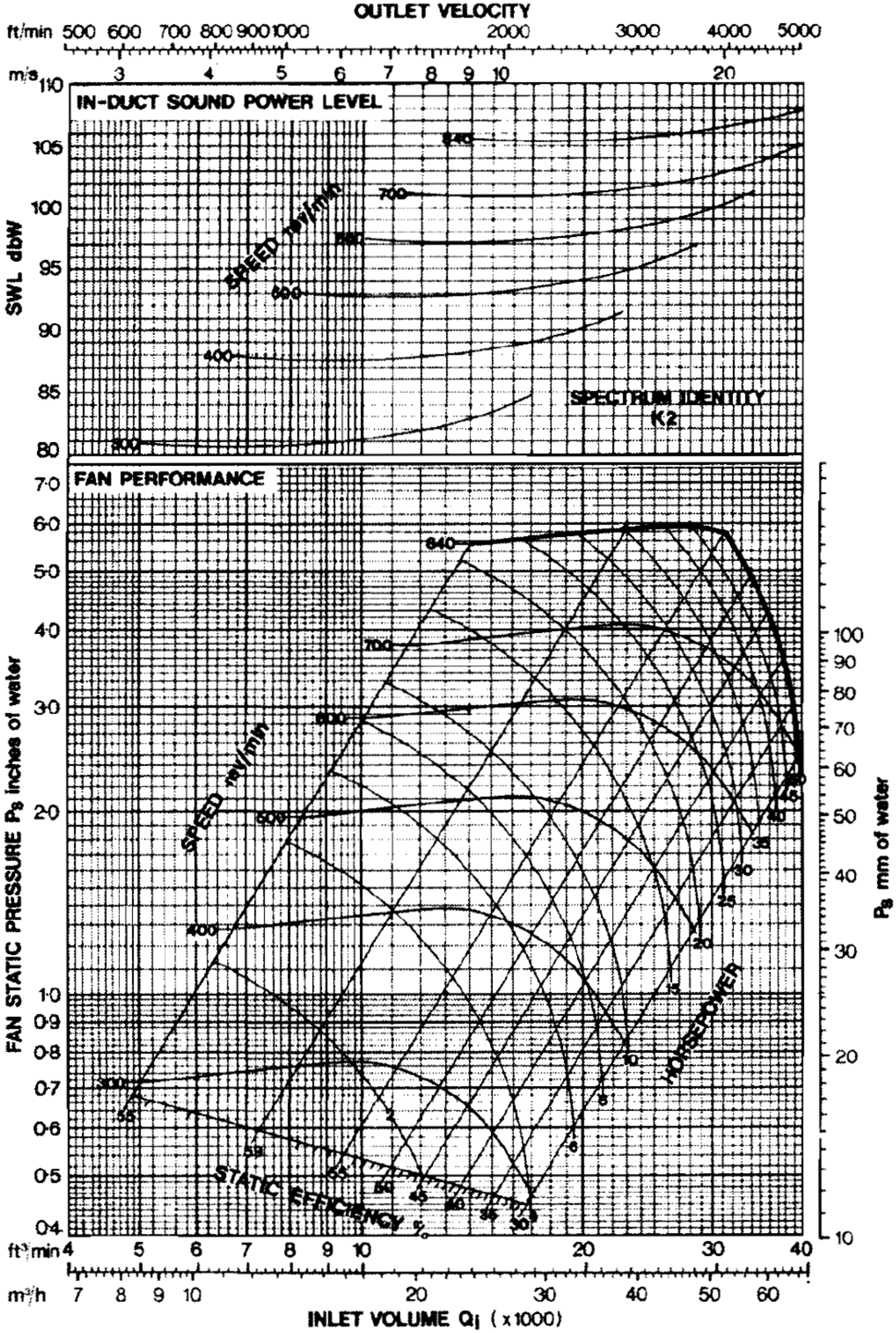

(الف)


(ب)


(ج)


(د)

Slide#26- Turbomachinery Course- FANS/ CHARACTERISTIC CURVES



Slide#27- Turbomachinery Course- FANS/ CHARACTERISTIC CURVES

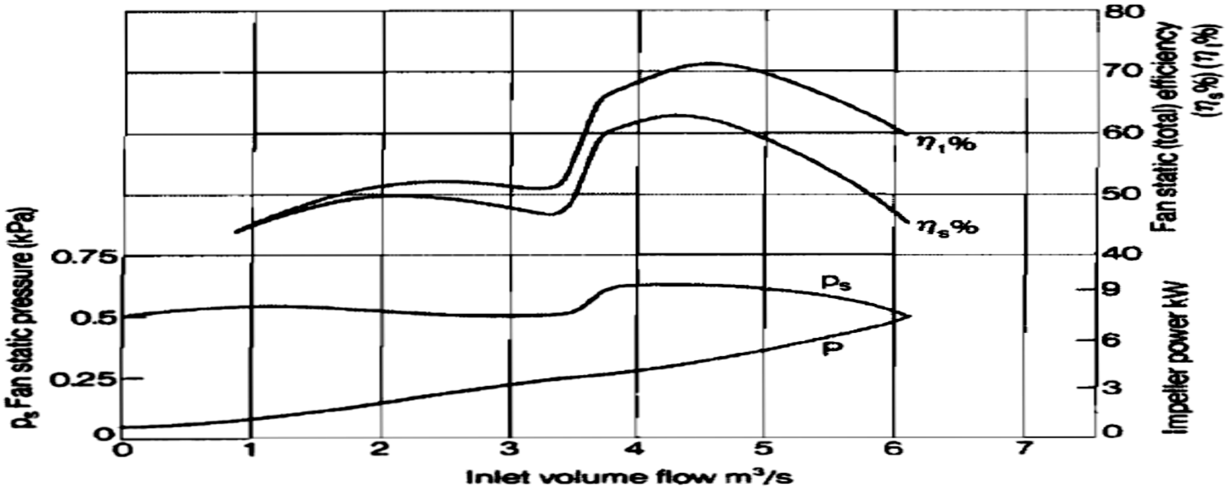


Figure 1.61 Forward curved fan — typical characteristic curves

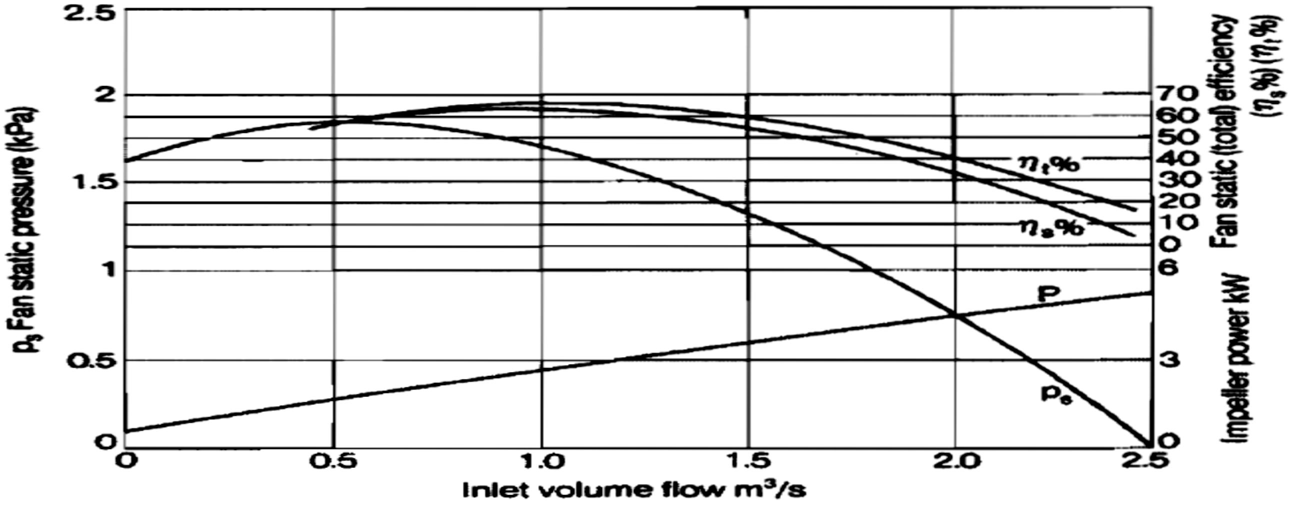


Figure 1.65 Shrouded radial fan — typical characteristic curves

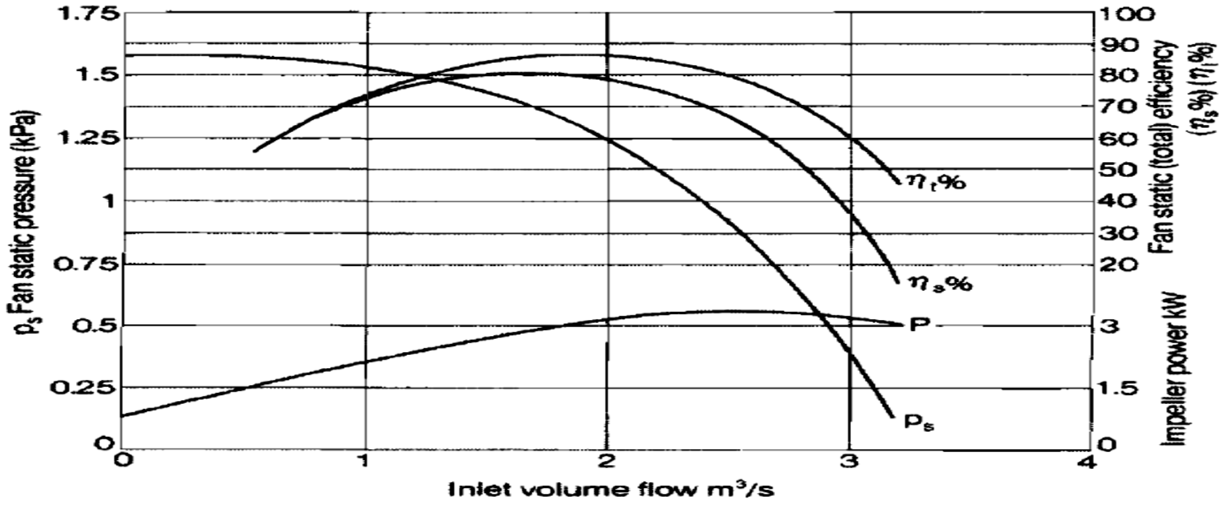
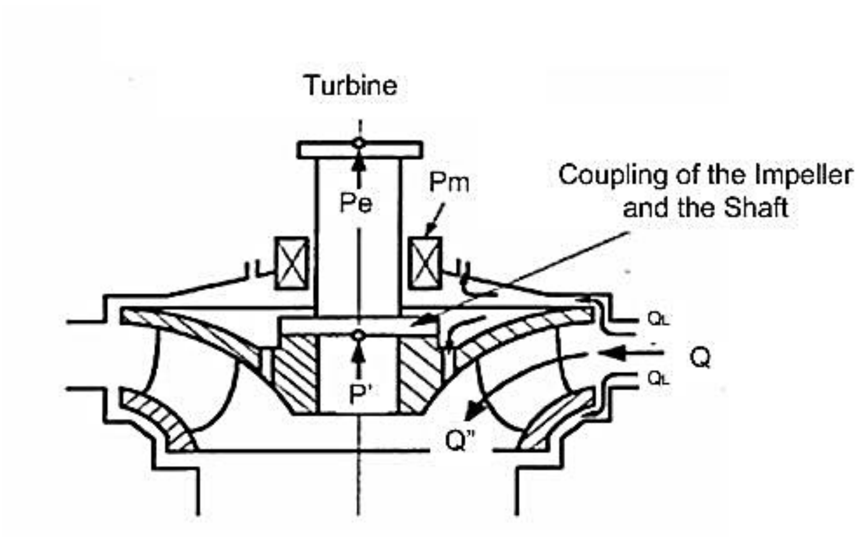


Figure 1.73 Backward curved fan — typical characteristic curves

Slide#28- Turbomachinery Course- TURBINE/ LOSSES



$$Q = Q" + Q_L$$

$$P = E.(\rho Q)$$

$$P_s = P' - P_m$$

$$P" = P' + P_D$$

$$\eta_V = \frac{Q"}{Q} = \frac{Q"}{Q" + Q_L}$$

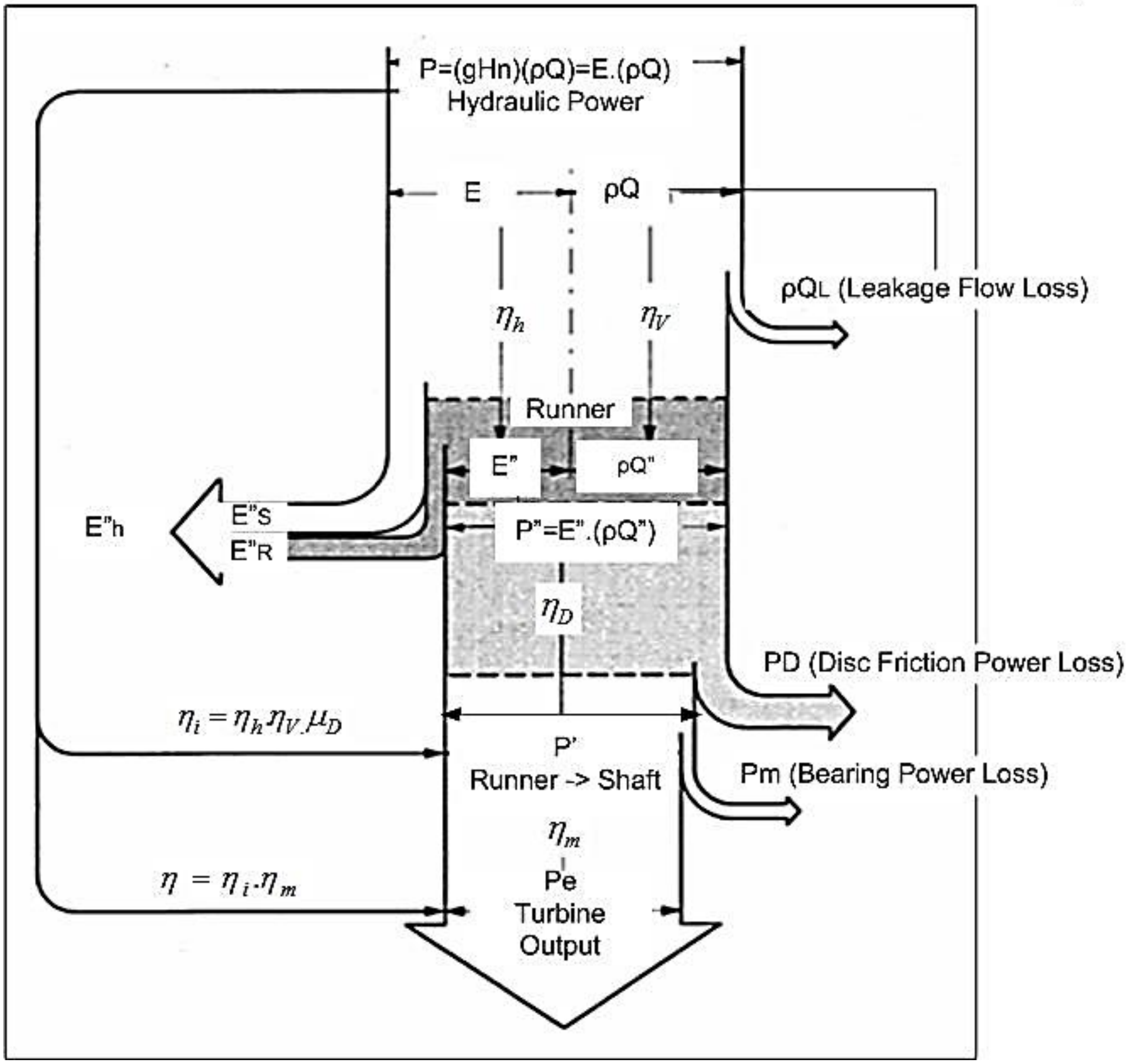
$$\eta_h = \frac{E"}{E}$$

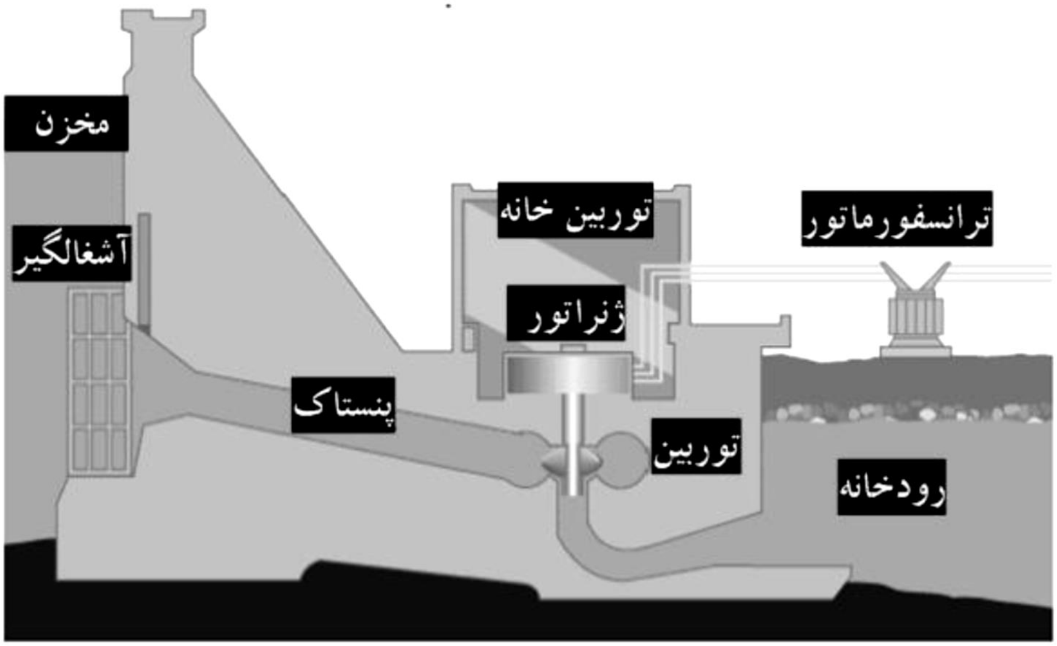
$$\eta_D = \frac{P'}{P"} = \frac{P'}{P' + P_D}$$

$$\eta_m = \frac{P_s}{P'} = \frac{P_s}{P_s + P_m}$$

$$\eta_{\ i} = \eta_h \eta_V . \eta_D = \frac{P'}{P}$$

$$\eta = \eta_i . \eta_m = \frac{P_s}{P}$$





شکل ۹-۲- اجزاء یک نیروگاه آبی

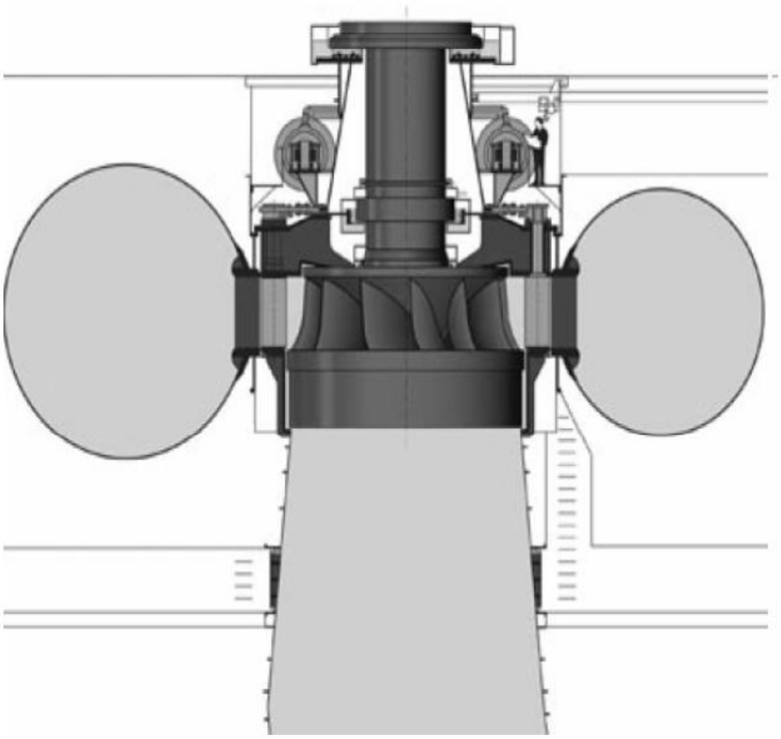
جدول۳-۲- مشخصات چند نیروگاه آبی کشور با ظرفیت بالای ۱۰۰ مگاوات

نام نیروگاه	نوع توربین	ظرفیت (مگاوات)	محل جغرافیائی
دز	فرانسیس	۵۲۰	خوزستان- رودخانه دز
سیاه بیشه (تلمبه- ذخیره‌ای)	فرانسیس	۱۰۰۰	مازندران- سیاه بیشه
سیمره	فرانسیس	۴۸۰	ایلام- رودخانه سیمره
شهید عباسپور	فرانسیس	۱۰۰۰	خوزستان- رودخانه کارون
کارون ۱	فرانسیس	۱۰۰۰	خوزستان- رودخانه کارون
کارون ۳	فرانسیس	۲۰۰۰	خوزستان- رودخانه کارون
کارون ۴	فرانسیس	۱۰۰۰	چهارمحال و بختیاری- رودخانه کارون
کرخه	فرانسیس	۴۰۰	خوزستان- رودخانه کرخه
گتوند علیا	فرانسیس	۲۰۰۰	خوزستان- رودخانه کارون
مارون	فرانسیس	۱۵۰	خوزستان- رودخانه مارون
مسجد سلیمان	فرانسیس	۲۰۰۰	خوزستان- رودخانه کارون

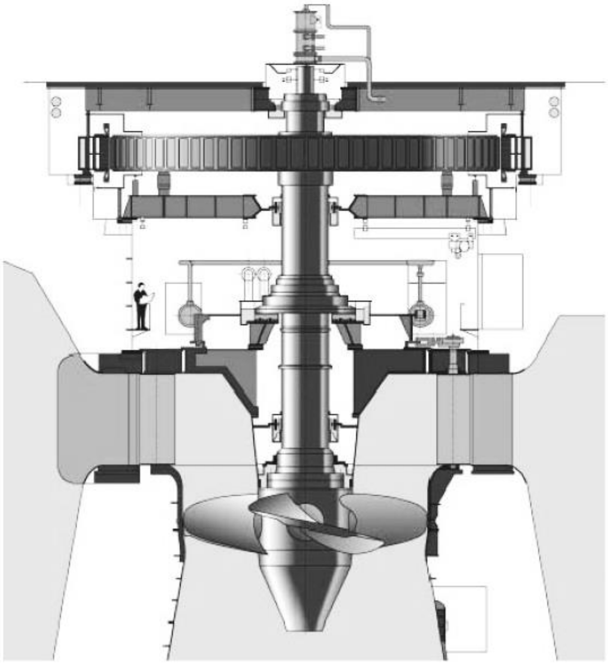
تقسیم بندی نیروگاههای ابی کوچک

قدرت تولیدی (کیلووات)	نوع نیروگاه
تا ۵۰	نیروگاه آبی ریز (micro)
۵۰ تا ۵۰۰	نیروگاه آبی خیلی کوچک (mini)
۵۰۰ تا ۵۰۰۰	نیروگاه آبی کوچک (small)
۵۰۰۰ تا ۵۰۰۰۰	نیروگاه آبی متوسط (medium)
>۵۰۰۰۰	نیروگاه آبی بزرگ (Large)

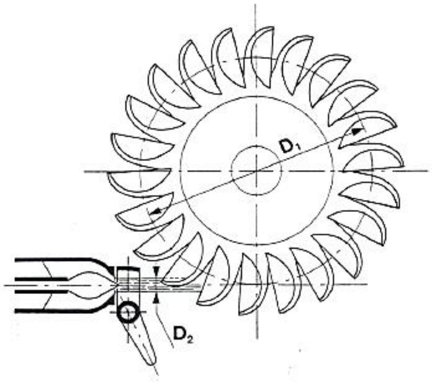
توربین فرانسیس



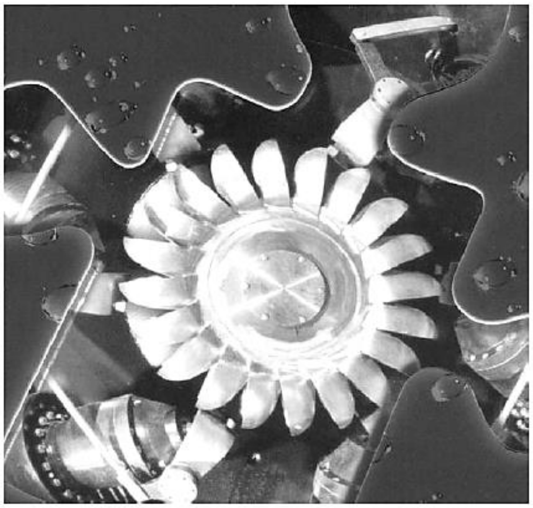
توربین کاپلان



توربین پلتون



شکل ۱-۳ – شکل شماتیک قسمت‌های اصلی توربین پلتون [۴]

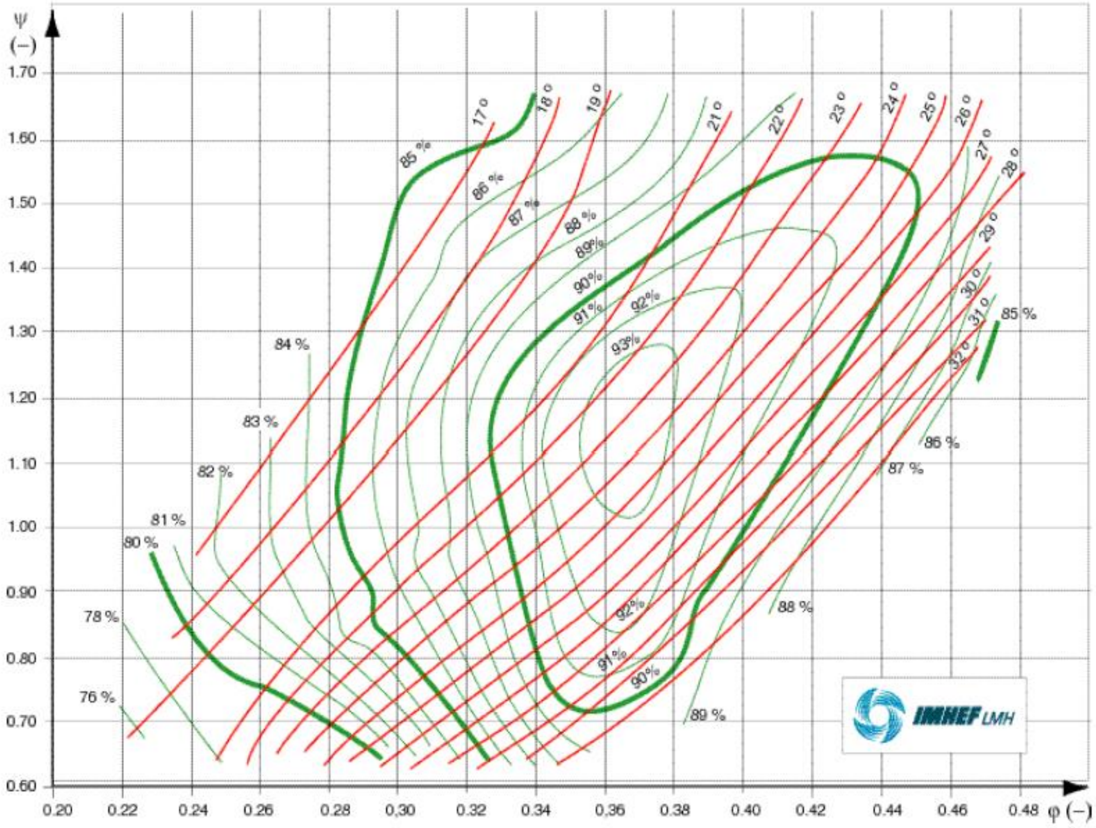


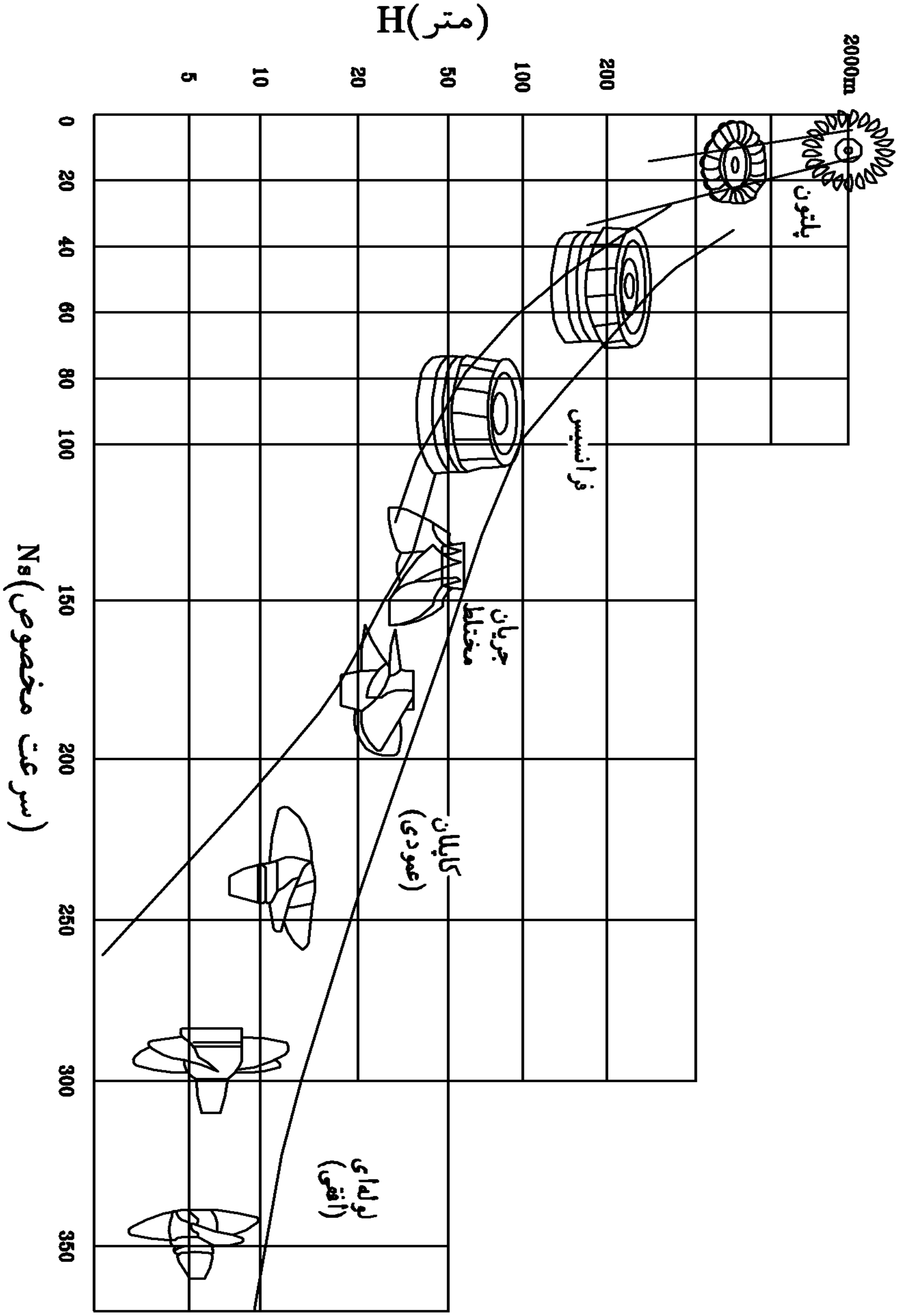
شکل ۲-۳– شکل چرخ و انژکتور توربین پلتون [۵]

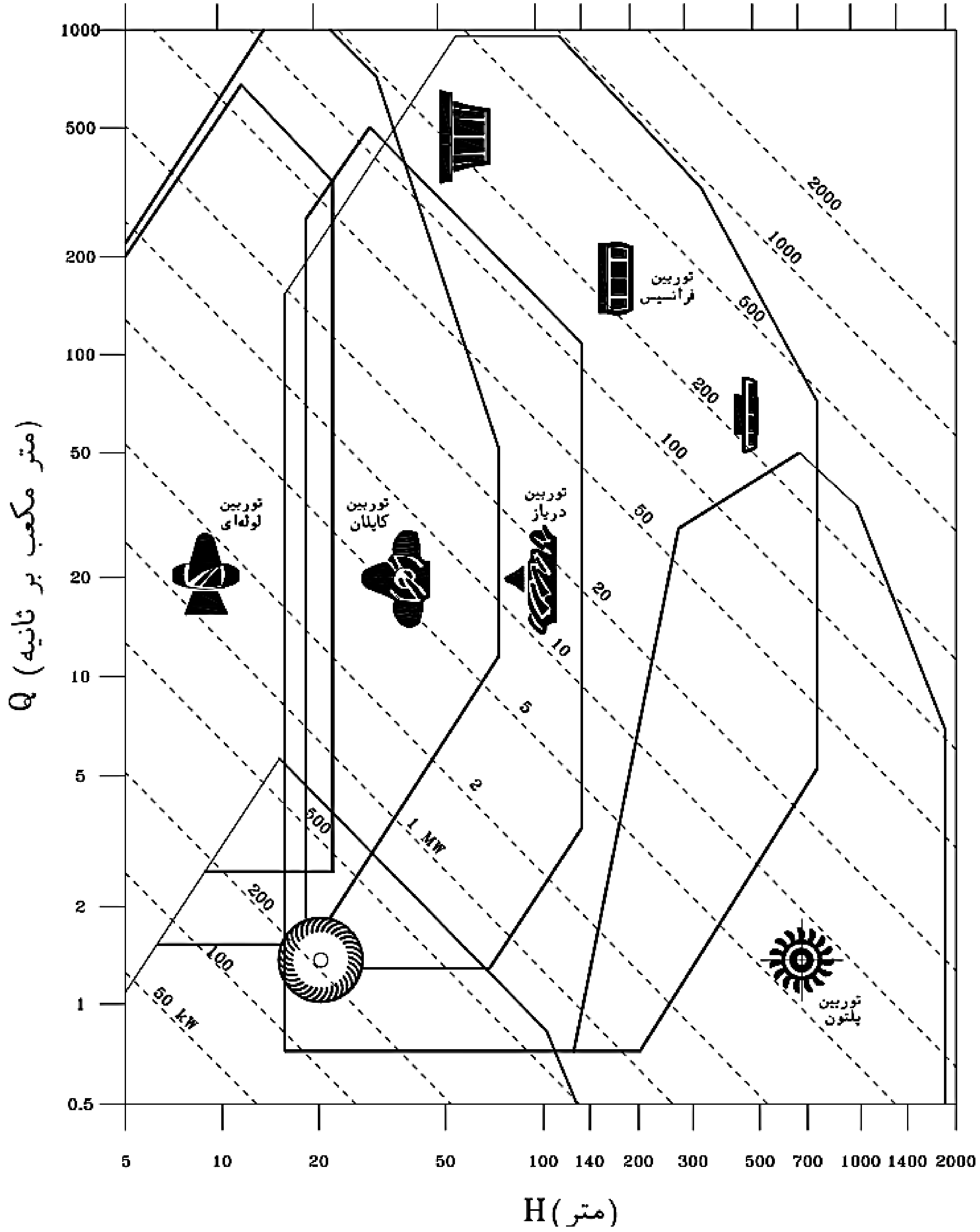
سرعت مخصوص(Ns)

نوع توربین	کند	متوسط	تند
پلتون	۱۵-۴	۳۰-۱۶	۷۰-۳۱
فرانسیس	۱۵۰-۶۰	۲۵۰-۱۵۱	۴۰۰-۲۵۱
کاپلان	۴۵۰-۳۰۰	۷۰۰-۴۵۱	۱۱۰۰-۷۰۱

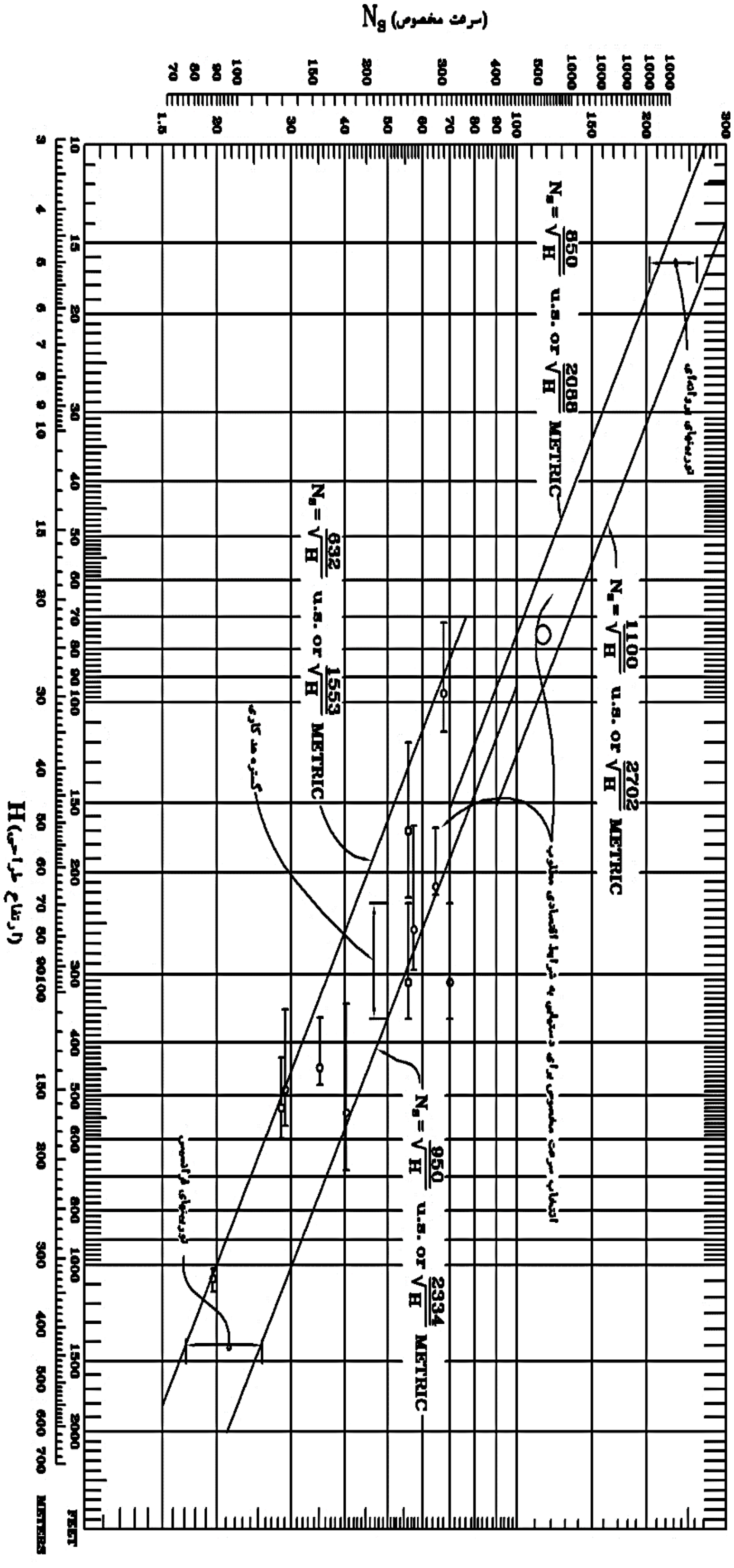
منحنی های مشخصه

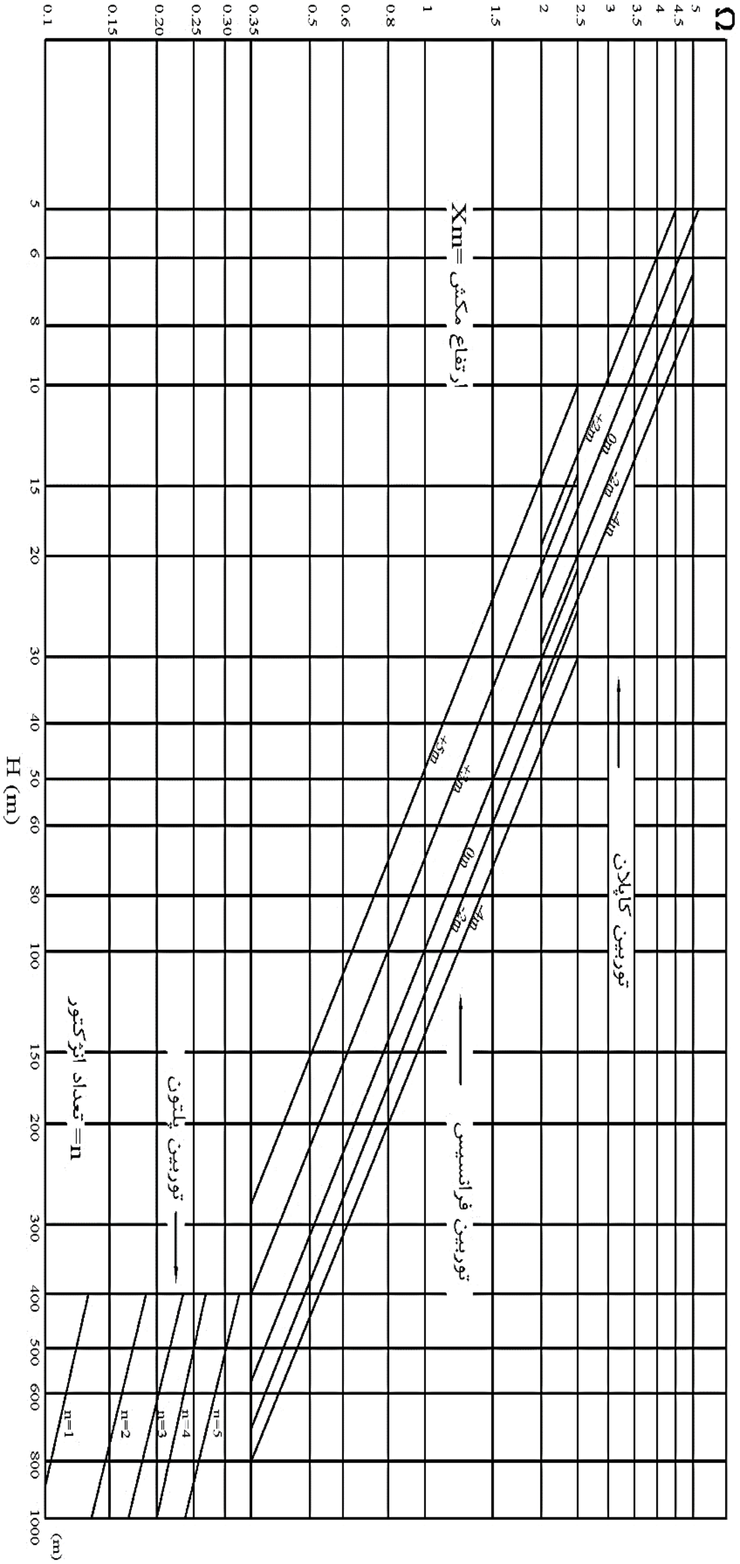


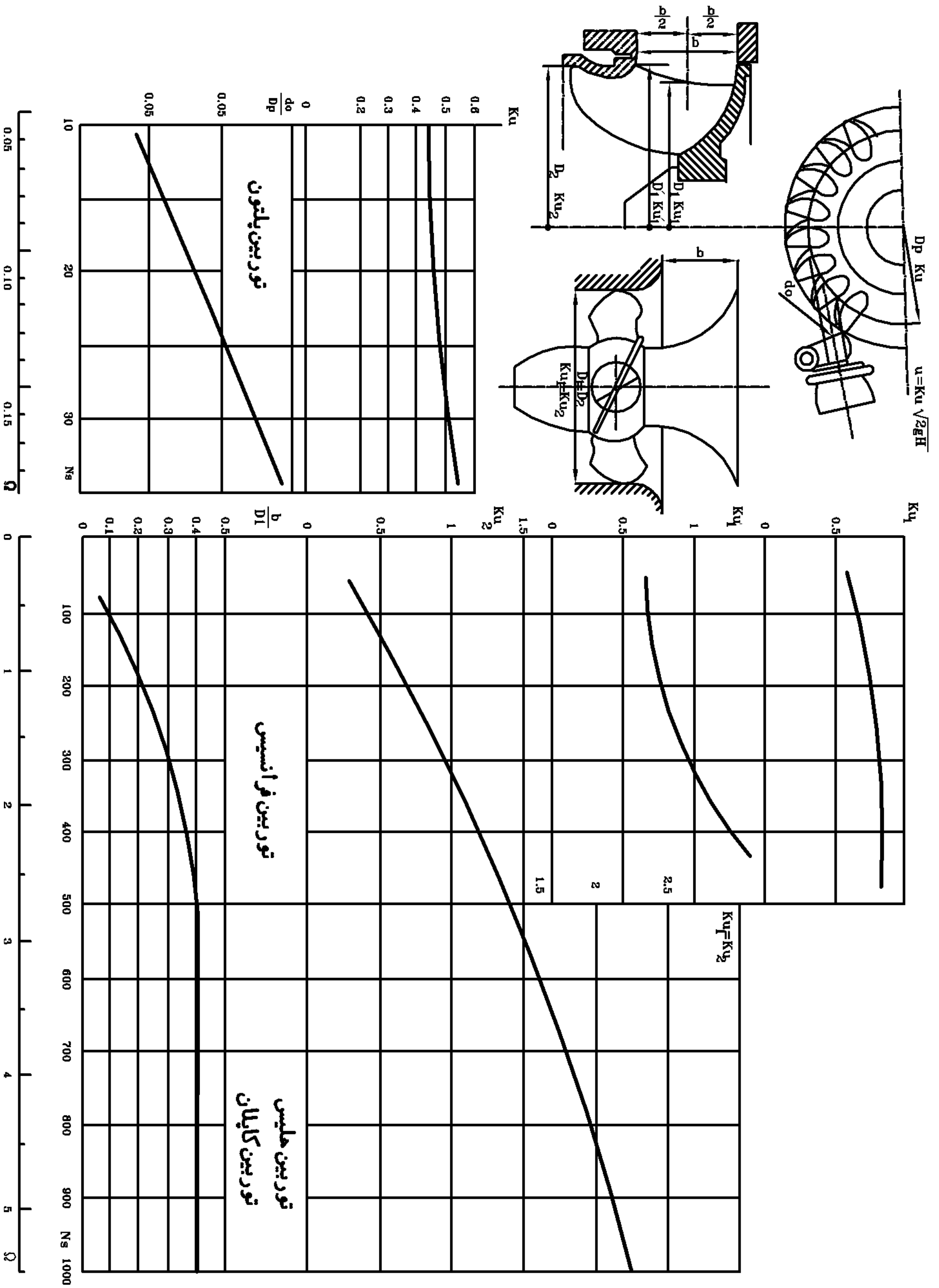

H(متر)
2000m
200
100
50
20
10
5
0
20
40
60
80
100
150
200
250
300
350
Ns(سرعت مخصوص)
پلتون
فرانسیس
جریان مختلط
کاپلان
(عمودی)
لوله‌ای
(افقی)


1000
500
200
100
50
20
10
5
2
1
0.5
Q (متر مکعب بر ثانیه)
5
10
20
50
100
140
200
300
500
700
1000
1400
2000
H (متر)
توربین لوله‌ای
توربین کاپلان
توربین درياز
توربین فرانسیس
توربین پلتون
2000
1000
500
200
100
50
20
10
5
2
1 MW
500
200
100
50 kW

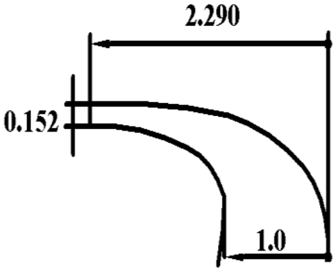
Slide#35- Turbomachinery Course- TURBINES/ SELECTION & DESIGN

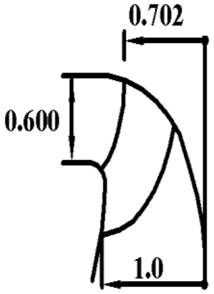





u=Ku $\sqrt{2gH}$
Dp Ku
d_0
$\frac{b}{2}$
$\frac{b}{2}$
b
D_1 Ku_1
D_1' Ku_1'
D_2 Ku_2
b
$D_1=D_2$
$Ku_1=Ku_2$
توربین پلتون
Ku
0.8
0.6
0.5
0.4
0.3
0.2
0
$\frac{d_0}{D_p}$
0.05
0.05
10
20
30
Ns
0.05
0.10
0.15
Ω
Ku_1
0.5
0
Ku_1'
1
0.5
0
Ku_2
1.5
1
0.5
0
$\frac{b}{D_1}$
0.5
0.4
0.3
0.2
0.1
0
2.5
2
1.5
$Ku_1=Ku_2$
توربین فرانسیس
توربین هلیس
توربین کاپلان
100
200
300
400
500
600
700
800
900
Ns 1000
0
1
2
3
4
5
Ω

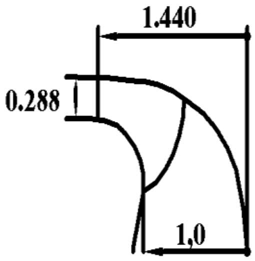
Ns=55

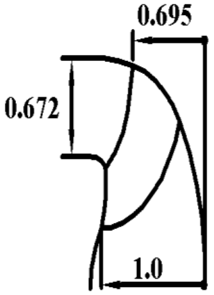




Ns=275

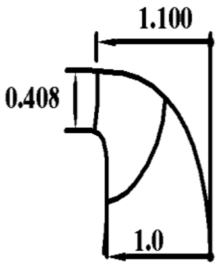
Ns=110

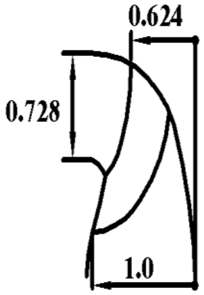




Ns=330

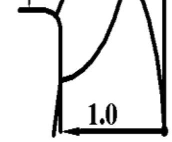
Ns=165





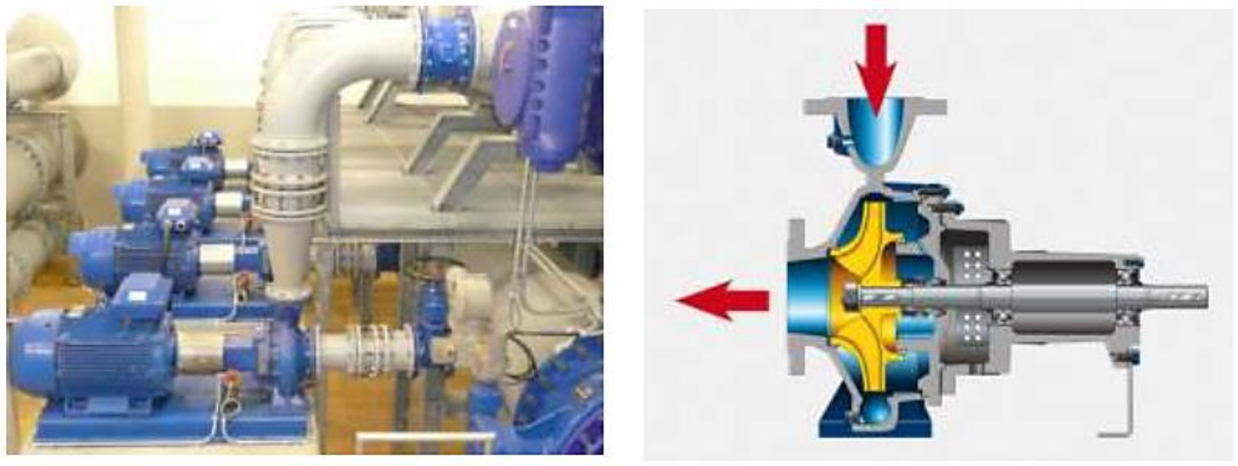
Ns=385

Ns=220

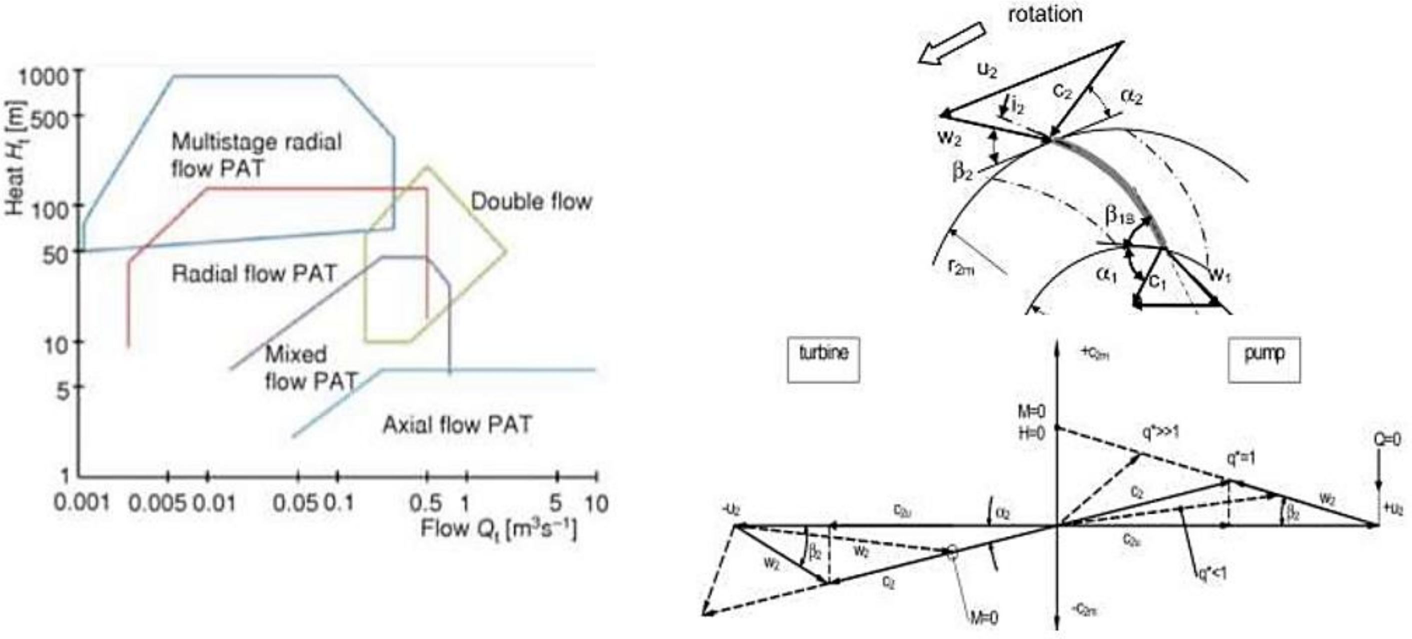


Ns=440

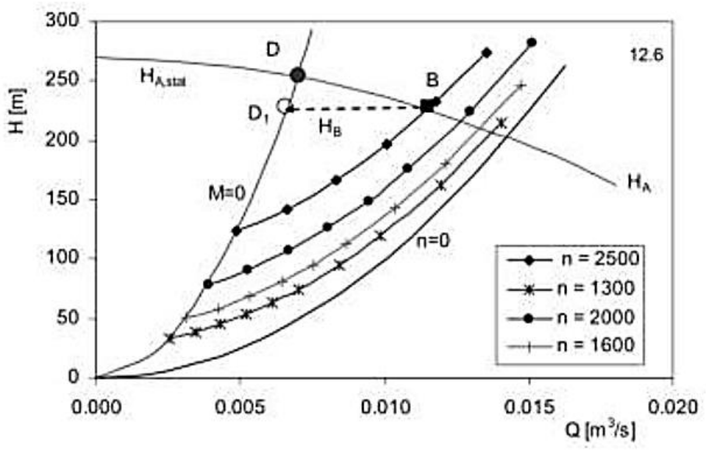
Slide#38- Turbomachinery Course- Pump as Turbine (PAT)



شماتیک PAT



چارت انتخاب و مثلث سرعت در PAT



منحنی مشخصه PAT و سیستم

Slide#39- Turbomachinery Course- Pump As Turbine (PAT)

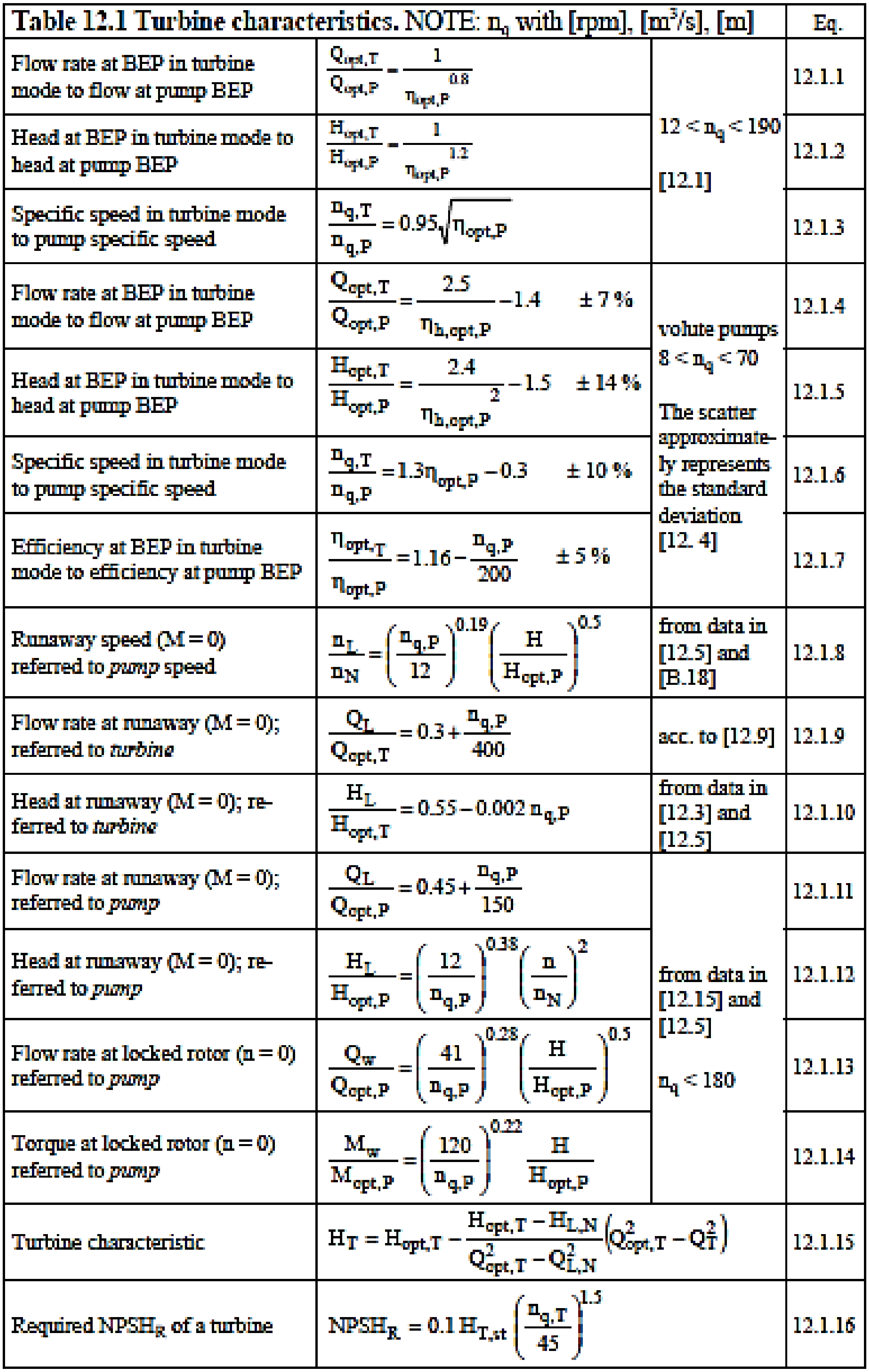


Table 12.1 Turbine characteristics. NOTE: n_q with [rpm], [m^3/s], [m]			Eq.
Flow rate at BEP in turbine mode to flow at pump BEP	$\frac{Q_{opt,T}}{Q_{opt,P}} = \frac{1}{\eta_{h,opt,P}^{0.8}}$	$12 < n_q < 190$ [12.1]	12.1.1
Head at BEP in turbine mode to head at pump BEP	$\frac{H_{opt,T}}{H_{opt,P}} = \frac{1}{\eta_{h,opt,P}^{1.2}}$		12.1.2
Specific speed in turbine mode to pump specific speed	$\frac{n_{q,T}}{n_{q,P}} = 0.95\sqrt{\eta_{opt,P}}$		12.1.3
Flow rate at BEP in turbine mode to flow at pump BEP	$\frac{Q_{opt,T}}{Q_{opt,P}} = \frac{2.5}{\eta_{h,opt,P}} - 1.4 \quad \pm 7\,\%$	volute pumps $8 < n_q < 70$ The scatter approximately represents the standard deviation [12. 4]	12.1.4
Head at BEP in turbine mode to head at pump BEP	$\frac{H_{opt,T}}{H_{opt,P}} = \frac{2.4}{\eta_{h,opt,P}^{2}} - 1.5 \quad \pm 14\,\%$		12.1.5
Specific speed in turbine mode to pump specific speed	$\frac{n_{q,T}}{n_{q,P}} = 1.3\eta_{opt,P} - 0.3 \quad \pm 10\,\%$		12.1.6
Efficiency at BEP in turbine mode to efficiency at pump BEP	$\frac{\eta_{opt,T}}{\eta_{opt,P}} = 1.16 - \frac{n_{q,P}}{200} \quad \pm 5\,\%$		12.1.7
Runaway speed (M = 0) referred to *pump* speed	$\frac{n_L}{n_N} = \left(\frac{n_{q,P}}{12}\right)^{0.19}\left(\frac{H}{H_{opt,P}}\right)^{0.5}$	from data in [12.5] and [B.18]	12.1.8
Flow rate at runaway (M = 0); referred to *turbine*	$\frac{Q_L}{Q_{opt,T}} = 0.3 + \frac{n_{q,P}}{400}$	acc. to [12.9]	12.1.9
Head at runaway (M = 0); referred to *turbine*	$\frac{H_L}{H_{opt,T}} = 0.55 - 0.002\, n_{q,P}$	from data in [12.3] and [12.5]	12.1.10
Flow rate at runaway (M = 0); referred to *pump*	$\frac{Q_L}{Q_{opt,P}} = 0.45 + \frac{n_{q,P}}{150}$	from data in [12.15] and [12.5] $n_q < 180$	12.1.11
Head at runaway (M = 0); referred to *pump*	$\frac{H_L}{H_{opt,P}} = \left(\frac{12}{n_{q,P}}\right)^{0.38}\left(\frac{n}{n_N}\right)^{2}$		12.1.12
Flow rate at locked rotor (n = 0) referred to *pump*	$\frac{Q_w}{Q_{opt,P}} = \left(\frac{41}{n_{q,P}}\right)^{0.28}\left(\frac{H}{H_{opt,P}}\right)^{0.5}$		12.1.13
Torque at locked rotor (n = 0) referred to *pump*	$\frac{M_w}{M_{opt,P}} = \left(\frac{120}{n_{q,P}}\right)^{0.22}\frac{H}{H_{opt,P}}$		12.1.14
Turbine characteristic	$H_T = H_{opt,T} - \frac{H_{opt,T} - H_{L,N}}{Q_{opt,T}^2 - Q_{L,N}^2}\left(Q_{opt,T}^2 - Q_T^2\right)$		12.1.15
Required $NPSH_R$ of a turbine	$NPSH_R = 0.1\, H_{T,st}\left(\frac{n_{q,T}}{45}\right)^{1.5}$		12.1.16

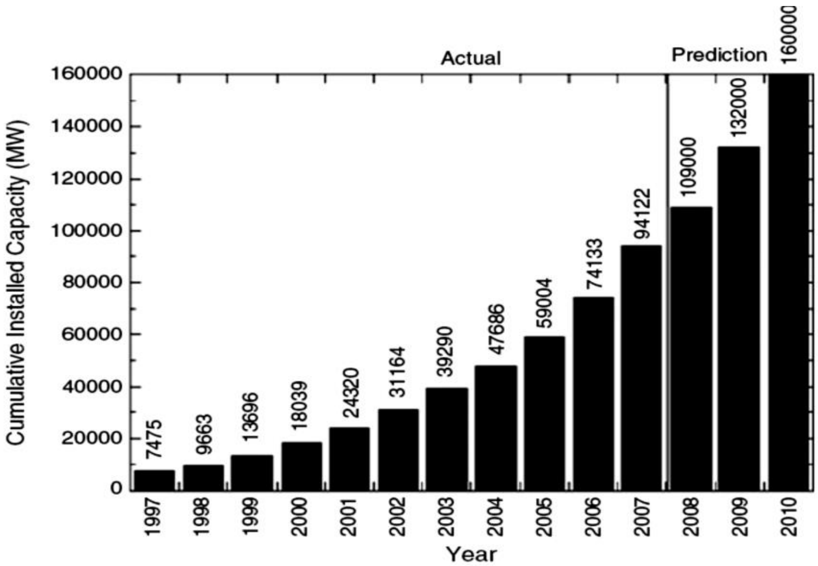


FIG 1. Projected increase in world wind power installed capacity

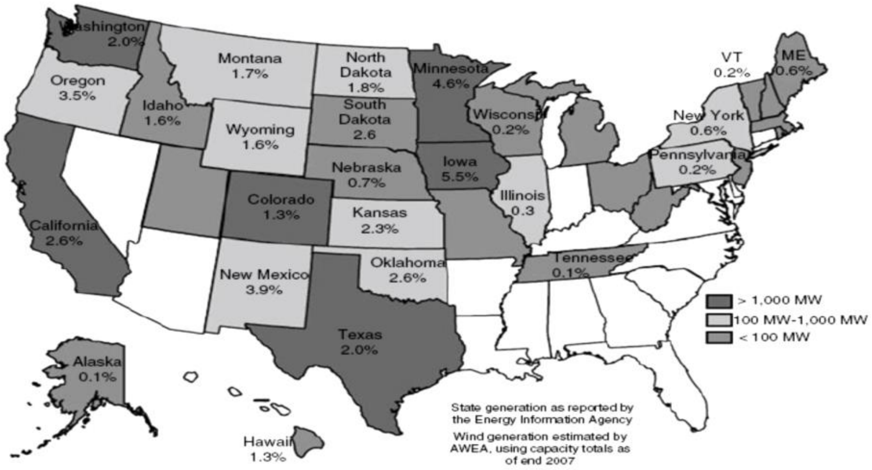
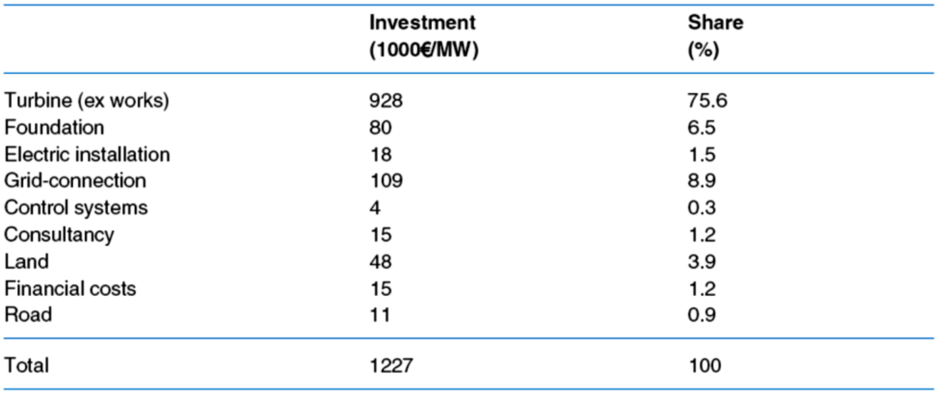


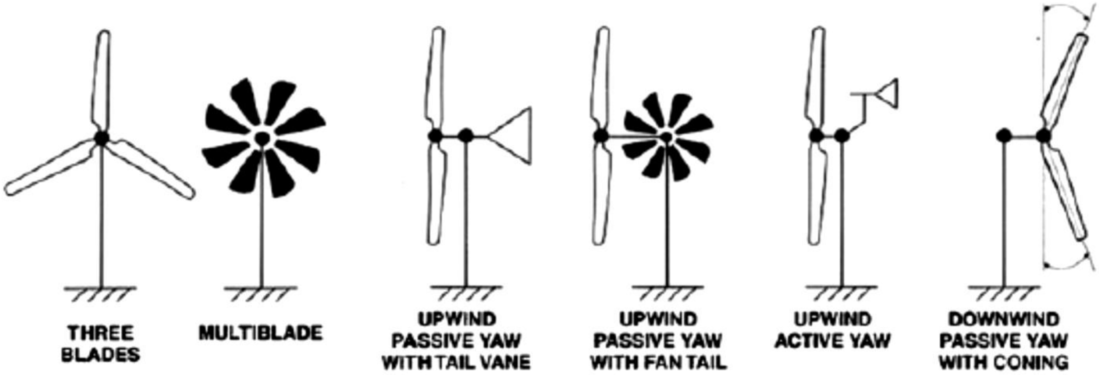
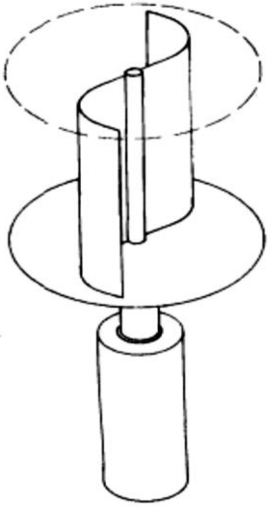
FIG 2. Percentage of electricity produced from wind energy by various states in the USA

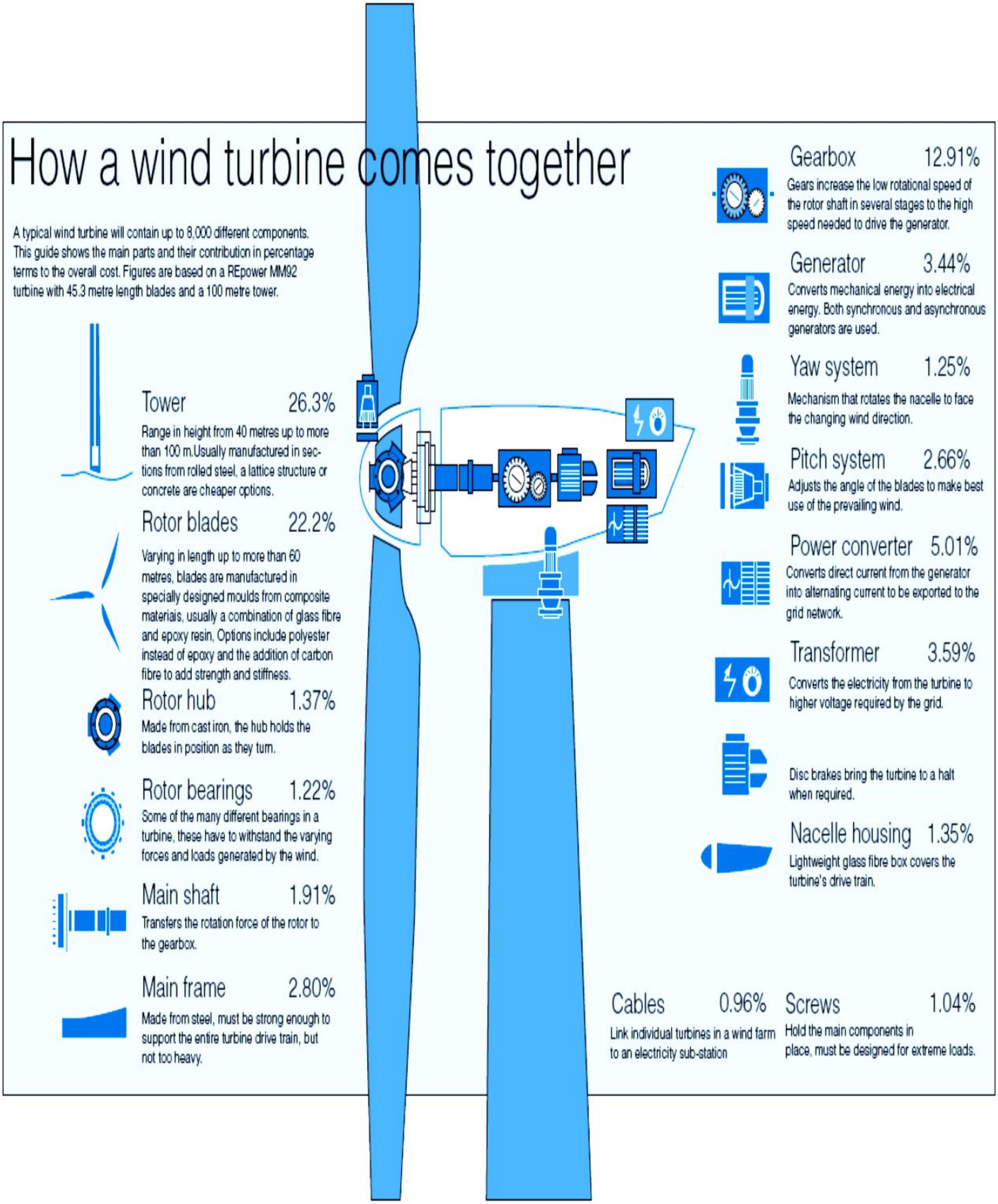


	Investment (1000€/MW)	Share (%)
Turbine (ex works)	928	75.6
Foundation	80	6.5
Electric installation	18	1.5
Grid-connection	109	8.9
Control systems	4	0.3
Consultancy	15	1.2
Land	48	3.9
Financial costs	15	1.2
Road	11	0.9
Total	1227	100

TABLE 1. Cost structure (in €) of a typical 2MW wind turbine based on selected data for European wind turbine installations (2006)

Slide#41- Turbomachinery Course- WIND TURBINES

HAWT			
HAWT			
VAWT			



How a wind turbine comes together

A typical wind turbine will contain up to 8,000 different components. This guide shows the main parts and their contribution in percentage terms to the overall cost. Figures are based on a REpower MM92 turbine with 45.3 metre length blades and a 100 metre tower.

Tower 26.3%

Range in height from 40 metres up to more than 100 m.Usually manufactured in sections from rolled steel, a lattice structure or concrete are cheaper options.

Rotor blades 22.2%

Varying in length up to more than 60 metres, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin, Options include polyester instead of epoxy and the addition of carbon fibre to add strength and stiffness.

Rotor hub 1.37%

Made from cast iron, the hub holds the blades in position as they turn.

Rotor bearings 1.22%

Some of the many different bearings in a turbine, these have to withstand the varying forces and loads generated by the wind.

Main shaft 1.91%

Transfers the rotation force of the rotor to the gearbox.

Main frame 2.80%

Made from steel, must be strong enough to support the entire turbine drive train, but not too heavy.

Gearbox 12.91%

Gears increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator.

Generator 3.44%

Converts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used.

Yaw system 1.25%

Mechanism that rotates the nacelle to face the changing wind direction.

Pitch system 2.66%

Adjusts the angle of the blades to make best use of the prevailing wind.

Power converter 5.01%

Converts direct current from the generator into alternating current to be exported to the grid network.

Transformer 3.59%

Converts the electricity from the turbine to higher voltage required by the grid.

Disc brakes bring the turbine to a halt when required.

Nacelle housing 1.35%

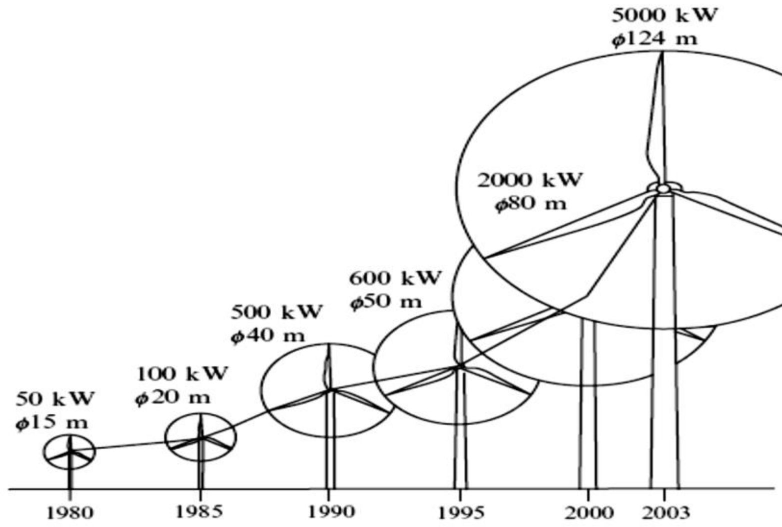
Lightweight glass fibre box covers the turbine's drive train.

Cables 0.96%

Link individual turbines in a wind farm to an electricity sub-station

Screws 1.04%

Hold the main components in place, must be designed for extreme loads.

The increase in the wind turbine power via increase in rotor diameter	

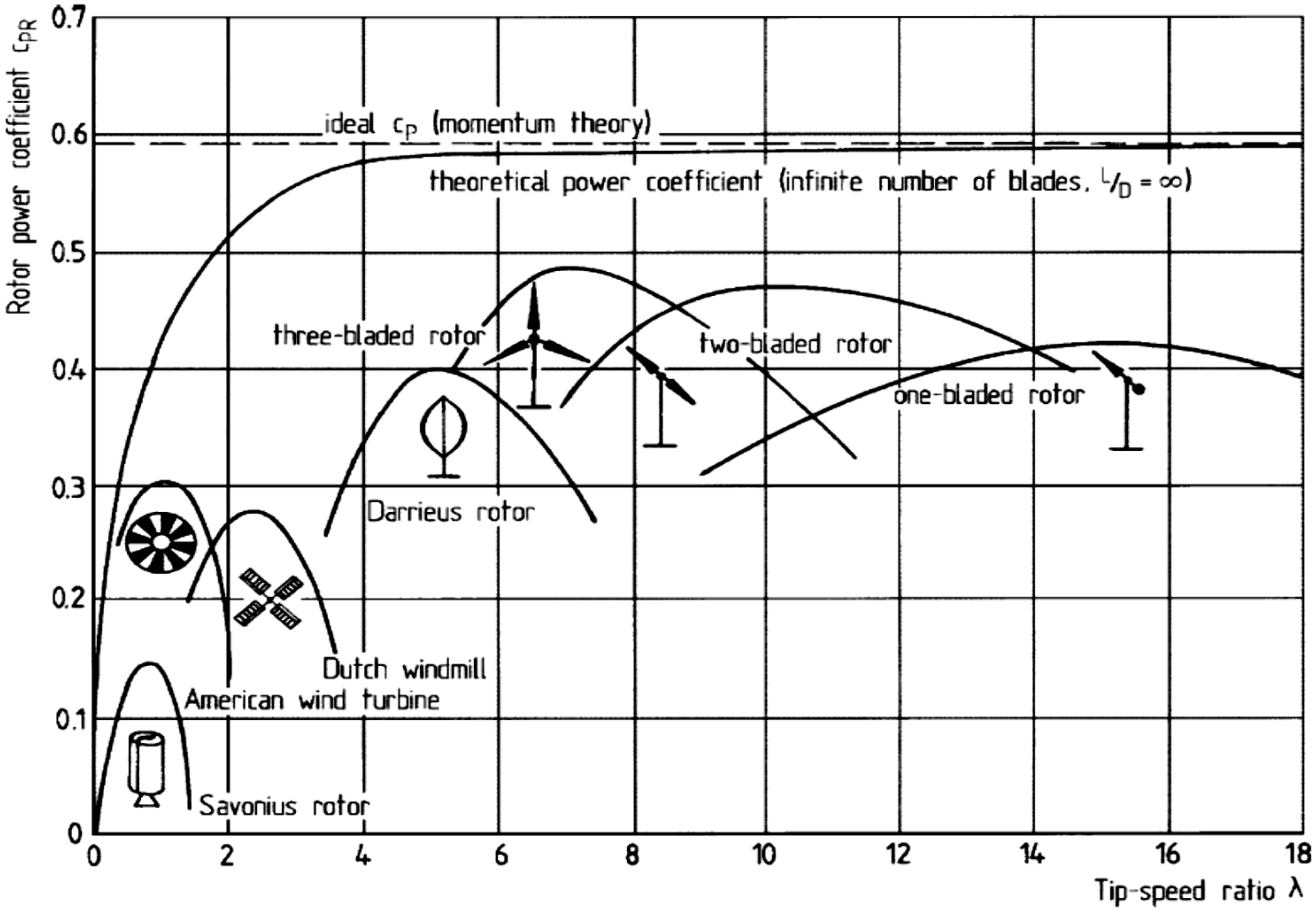
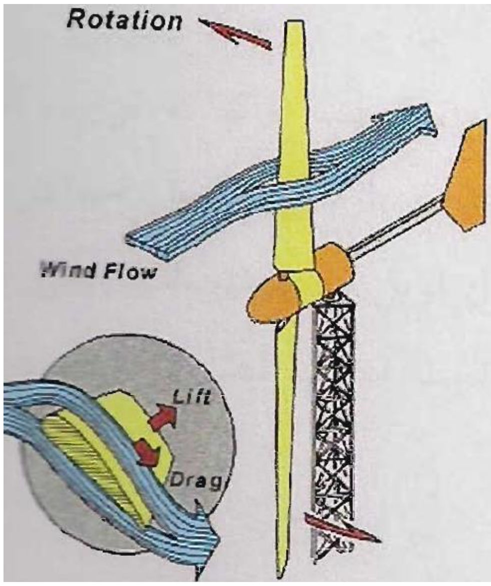
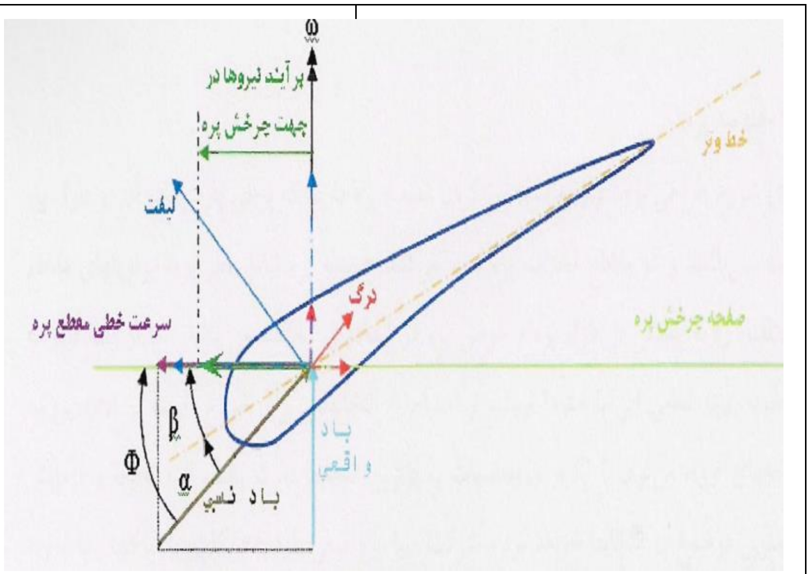


FIG 1. A plot of rotor power coefficient as a function of tip speed ratio for various turbines

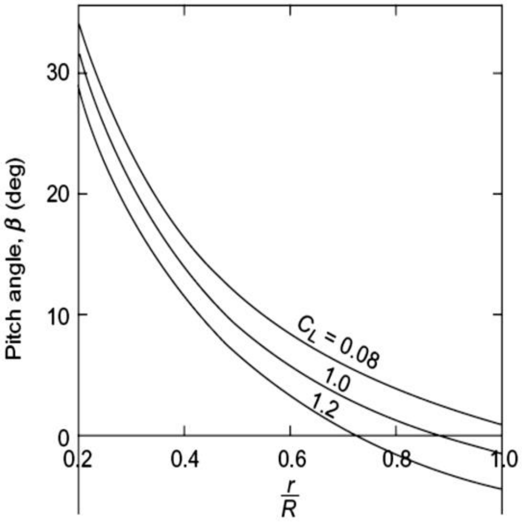
Slide#44- Turbomachinery Course- WIND TURBINES/ DESIGN

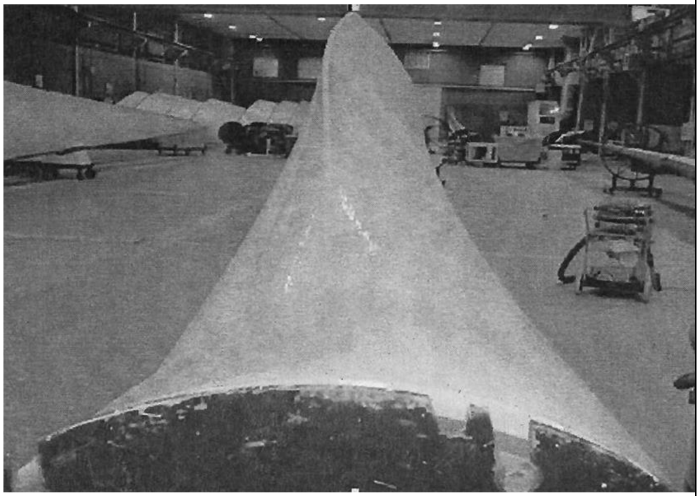
Cross section and Velocity Triangle of a wind turbine



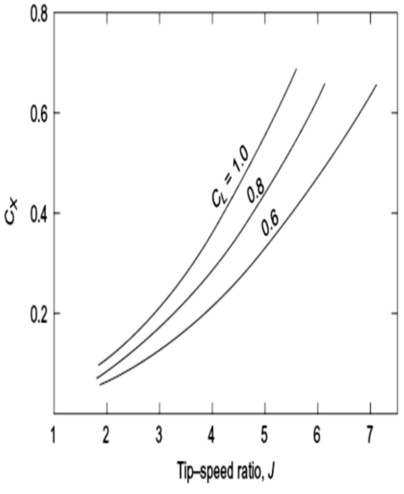


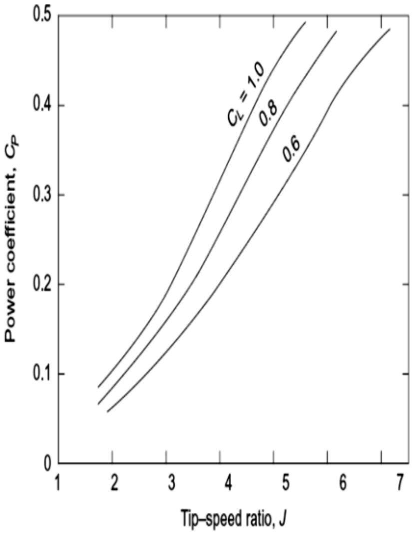
Effect of the Important variables on a Wind Turbine

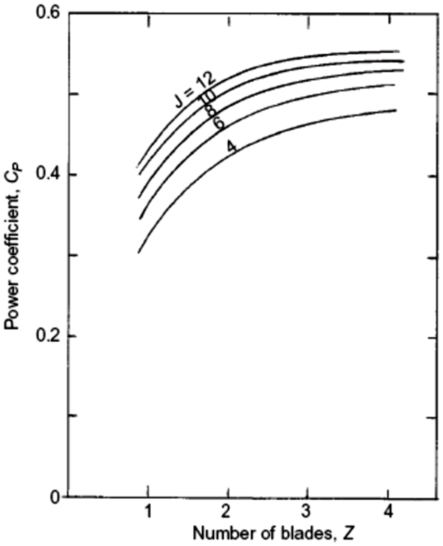




Effect of the Important variables on a Wind Turbine







Slide#45- Turbomachinery Course- WIND TURBINES/ DESIGN

- طول خط وتر در طول پره:

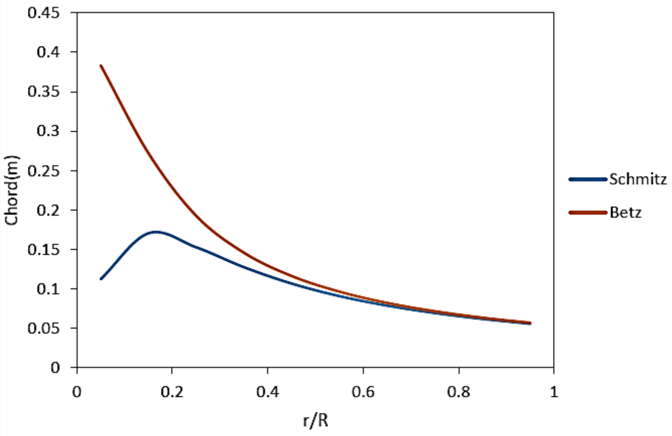
$$c(r)_{Schimtz} = \frac{1}{B}\frac{16\pi r}{C_L}\sin^2(\frac{1}{3}\tan^{-1}(\frac{R}{\lambda r}))$$

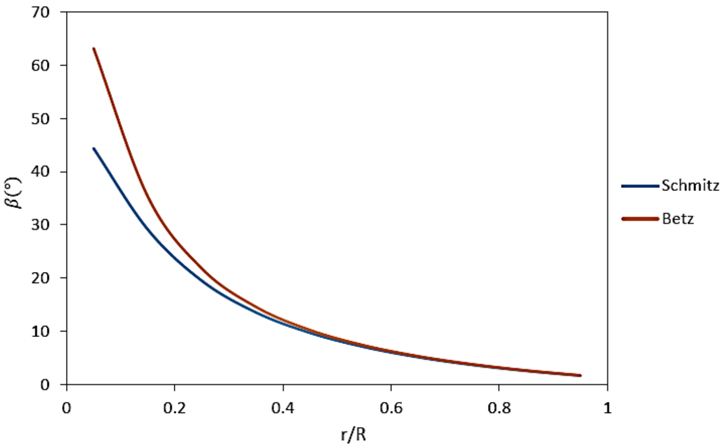
$$C(r)_{Betz} = \frac{16\pi R}{9BC_{L,D}}\frac{1}{\lambda\sqrt{\lambda^2(\frac{r}{R})^2+\frac{4}{9}}}$$

- زاویه پیچش در طول پره:

$$\beta(r)_{Schmitz} = \frac{2}{3}\tan^{-1}\frac{R}{\lambda r} - \alpha_D$$

$$\beta(r)_{Betz} = \tan^{-1}\frac{2R}{3r\,\lambda} - \alpha_D$$

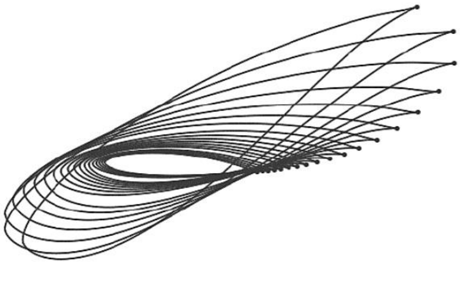


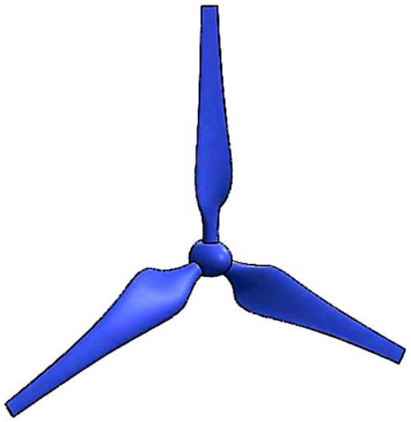


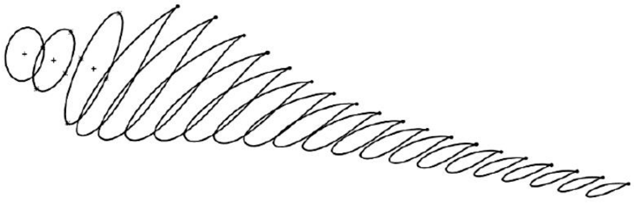
- چینش ایرفویل‌ها:

$$x_{cp} = \frac{c}{4} - \frac{M_{LE/4}}{L}$$

$$x_{cp} = (\frac{1}{4} - \frac{C_M}{4C_L})c$$

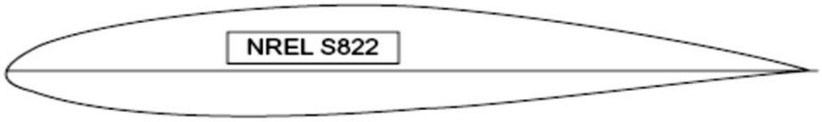






Slide#46- Turbomachinery Course- WIND TURBINES/ DESIGN

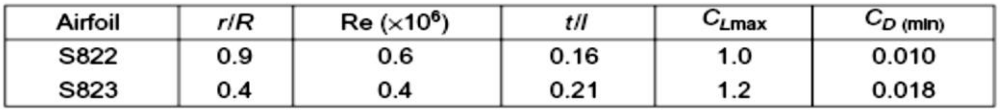
Thick aerofoil family for HAWTs of diameter 2 to 11m ($P = 2$ to 20kW)



Tip–region airfoil, 90% radius

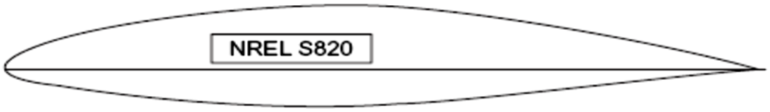
Root–region airfoil, 40% radius

Design Specifications

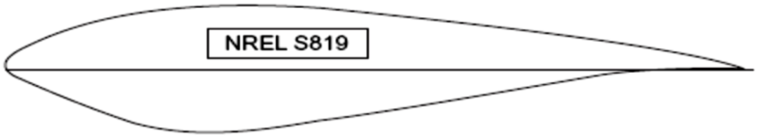


Airfoil	r/R	Re ($\times 10^6$)	t/l	$C_{L\max}$	$C_{D\,(\min)}$
S822	0.9	0.6	0.16	1.0	0.010
S823	0.4	0.4	0.21	1.2	0.018

Thick aerofoil family for HAWTs of diameter 11 to 21 m ($P = 20$ to 100kW)



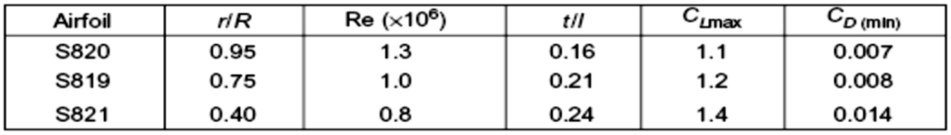
Tip–region airfoil, 95% radius



Primary outboard airfoil, 75% radius

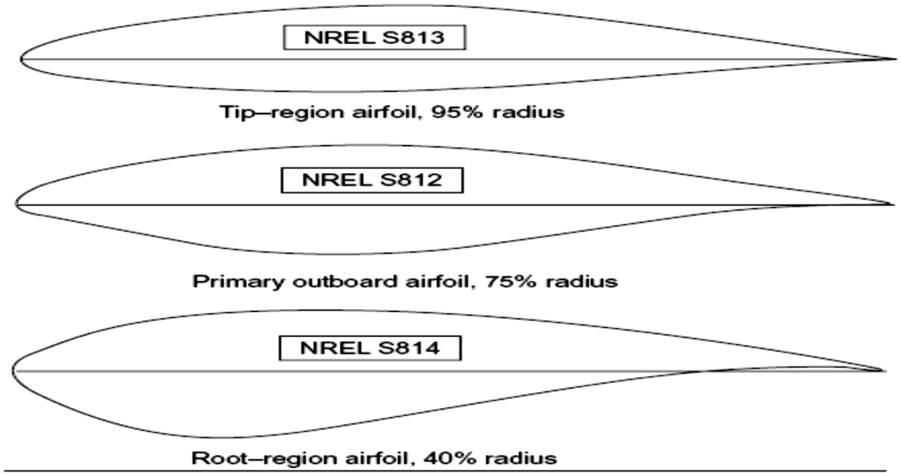
Root–region airfoil, 40% radius

Design Specifications



Airfoil	r/R	Re ($\times 10^6$)	t/l	$C_{L\max}$	$C_{D\,(\min)}$
S820	0.95	1.3	0.16	1.1	0.007
S819	0.75	1.0	0.21	1.2	0.008
S821	0.40	0.8	0.24	1.4	0.014

Thick aerofoil family for HAWTs of diameter 21 to 35 m (P = 100 to 400kW)



Tip–region airfoil, 95% radius

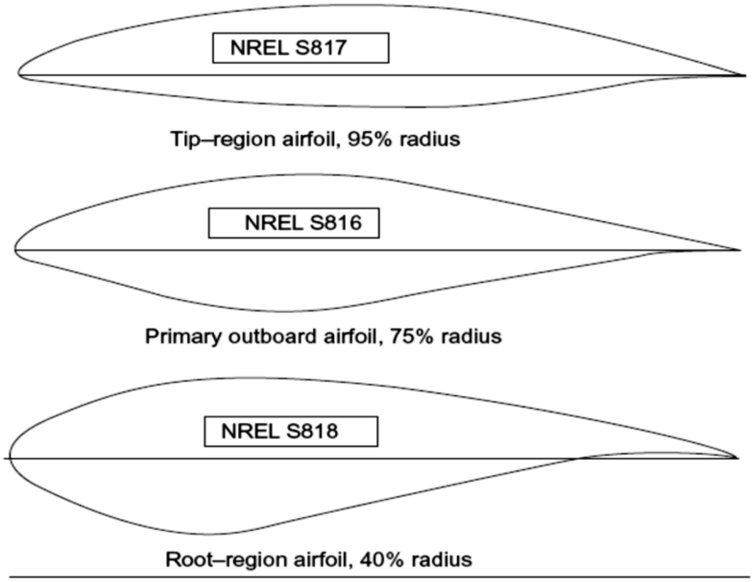
Primary outboard airfoil, 75% radius

Root–region airfoil, 40% radius

Design Specifications

Airfoil	r/R	Re ($\times 10^6$)	t/l	$C_{L\max}$	$C_{D\,(\min)}$
S813	0.95	2.0	0.16	1.1	0.007
S812	0.75	2.0	0.21	1.2	0.008
S814	0.40	1.5	0.24	1.3	0.012
S815	0.30	1.2	0.26	1.1	0.014

Thick aerofoil family for HAWTs with $D > 36$m (blade length 15 to 25 m, $P = 400$ to 1000 kW). (Courtesy NREL.)



Tip–region airfoil, 95% radius

Primary outboard airfoil, 75% radius

Root–region airfoil, 40% radius

Design Specifications

Airfoil	r/R	Re ($\times 10^6$)	t/l	$C_{L\max}$	$C_{D\,(\min)}$
S817	0.95	3.0	0.16	1.1	0.007
S816	0.75	4.0	0.21	1.2	0.008
S818	0.40	2.5	0.24	1.3	0.012

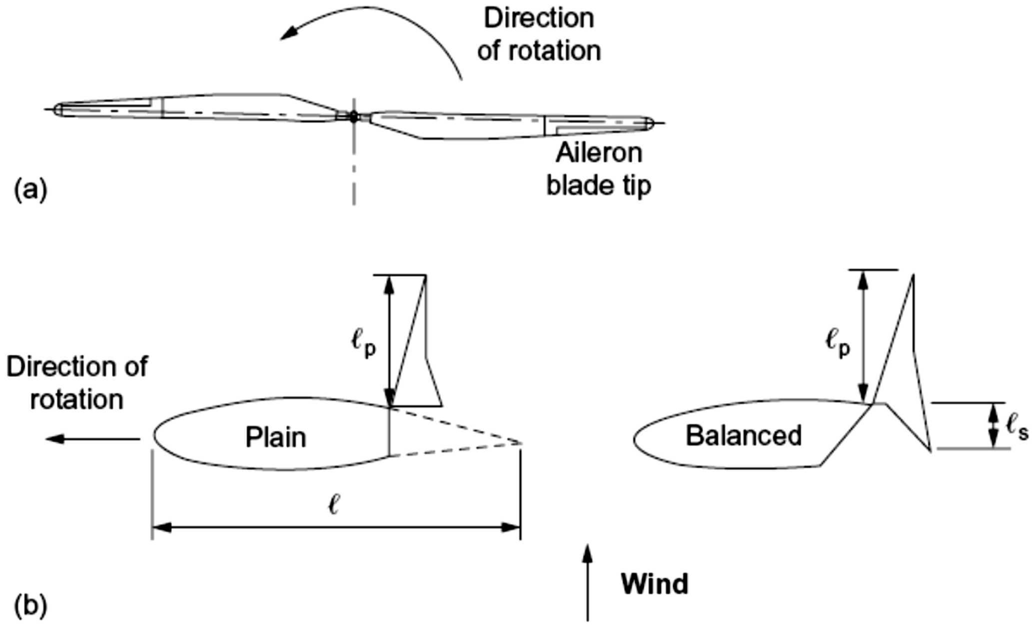
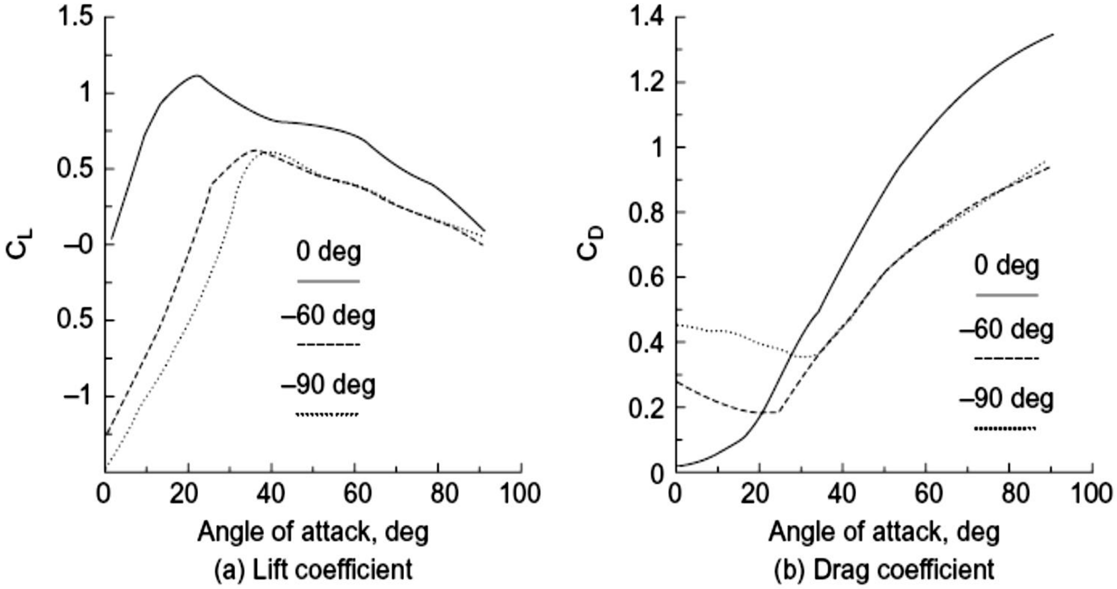
Aileron control surfaces: (a) showing position of ailerons on two-bladed rotor; (b) two types of aileron in fully deflected position (adapted from Miller and Sirocky 1985).	
Variation of (a) lift and (b) drag coefficients for the 38% chord ailerons when set at 0, -60 deg and at -90 deg. (Adapted from Savino *et al*. 1985. Courtesy of NASA.)	 (a) Lift coefficient (b) Drag coefficient

Table 10.3 Worldwide ocean energy projections: installed capacity

GW	2007	2010	2020	2025	2030	2040	2050
Very optimistic	0.4	1	20.4	40	61	149	309
Optimistic/Realistic	0.4	1	17	30	44	98	194
Pessimistic	0.4	0.4	4.8	7.4	10	20	40

Source: NEEDS project (2008)

Table 10.4 Worldwide ocean energy projections: generated electricity

TWh	2007	2010	2020	2025	2030	2040	2050
Very optimistic	1	3	70	151	231	593	1281
Optimistic/Realistic	1	3	51	101	152	372	773
Pessimistic	1	1	14	22	30	69	152

Source:NEEDS project (2008)

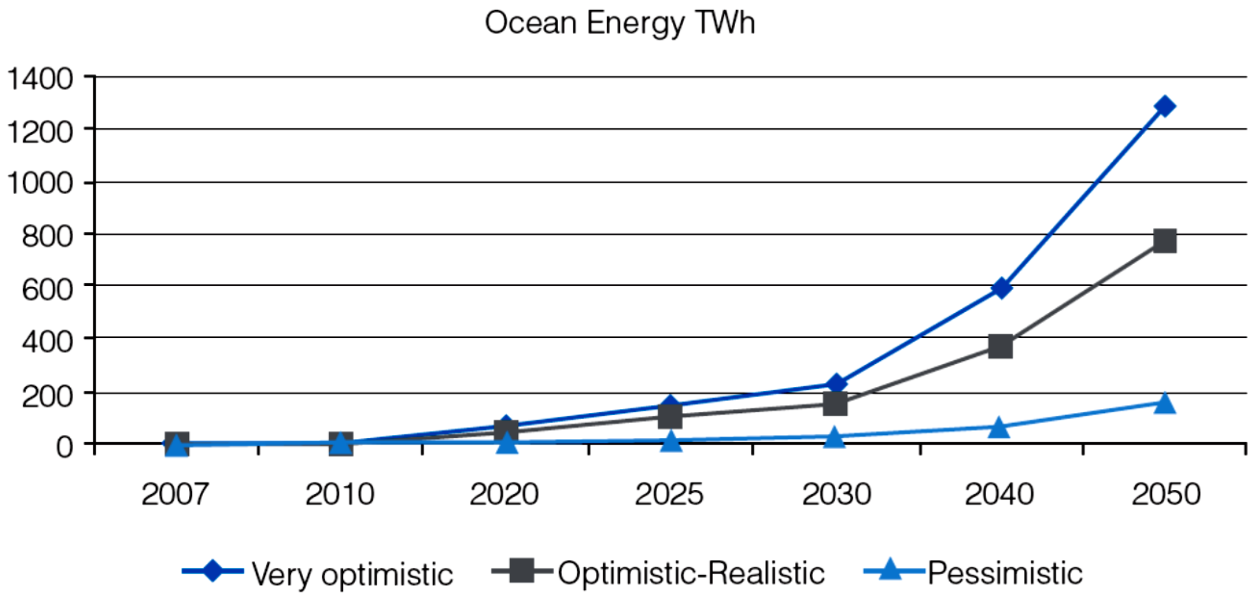
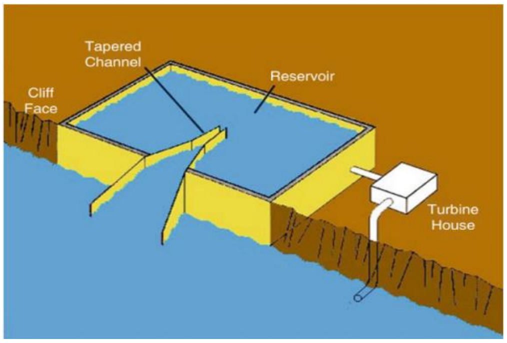
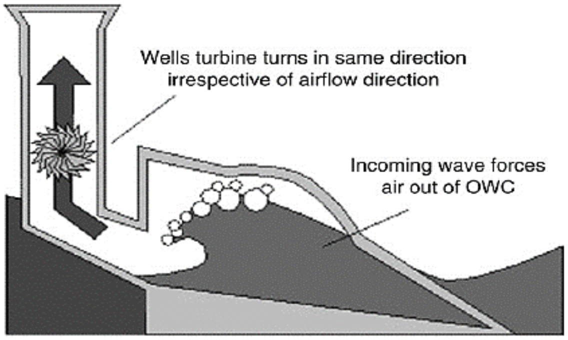
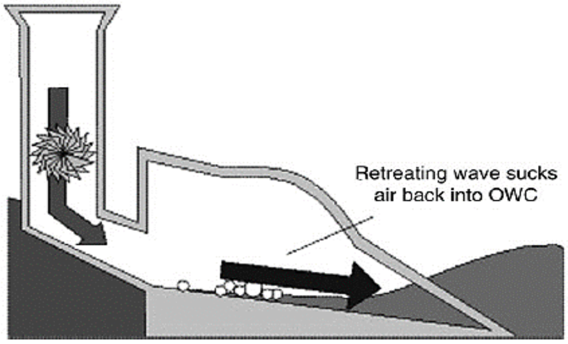
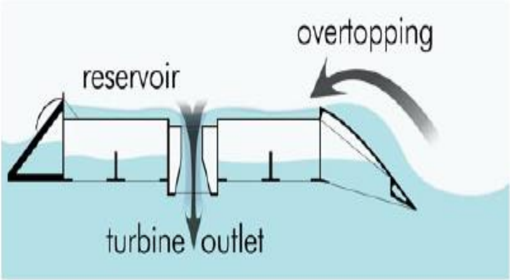
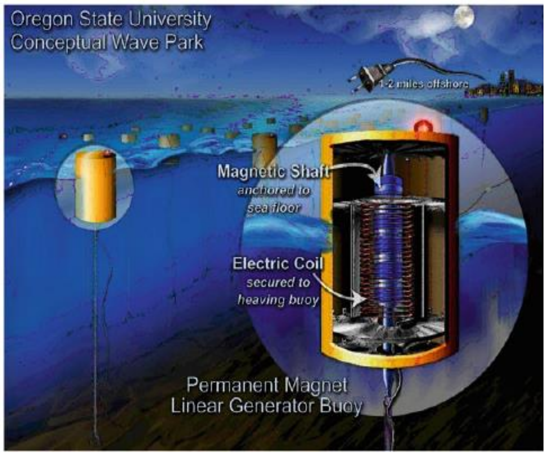
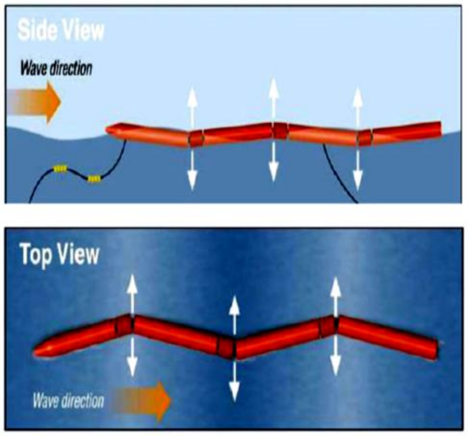


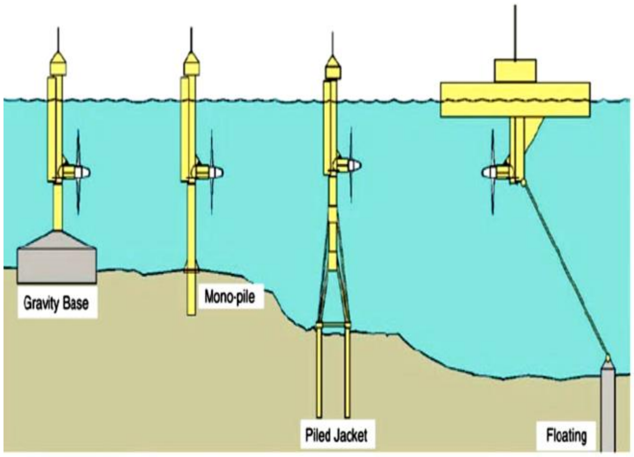
Figure 10.9 Worldwide ocean energy projections: generated electricity

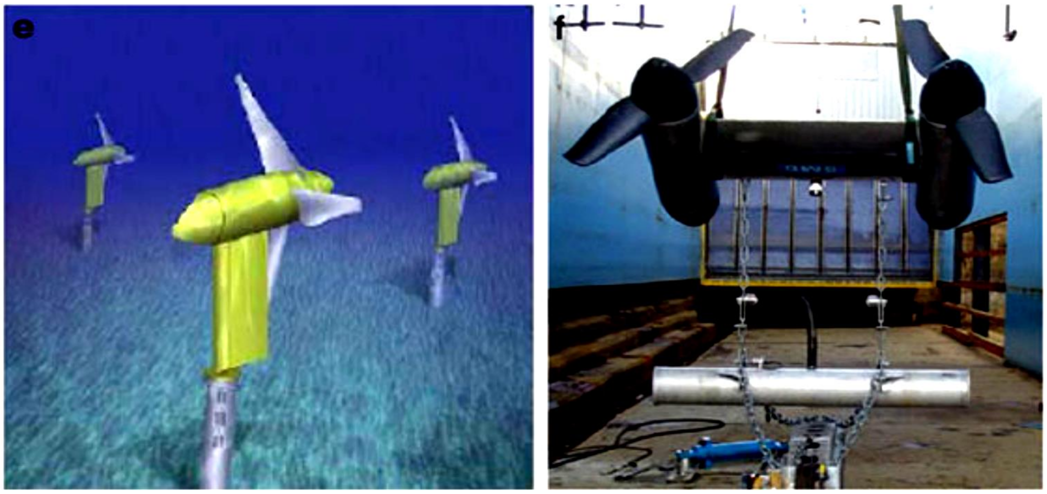
Slide#51- Turbomachinery Course- OCEAN ENERGY

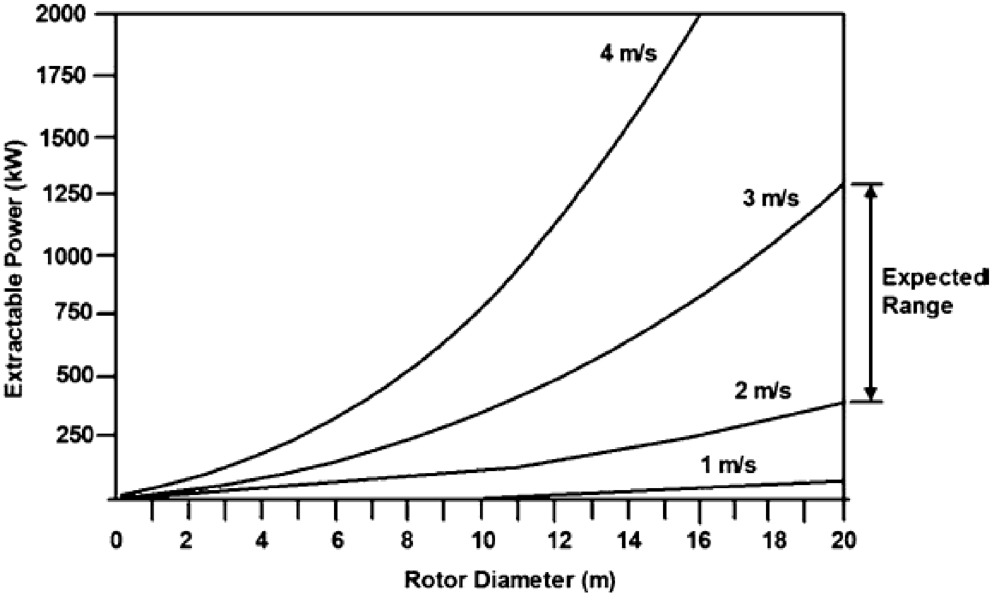
Harnessing of wave energy by TAPCHAN systems for power production, oscillating water column and overtopping		 
		
Floating device		

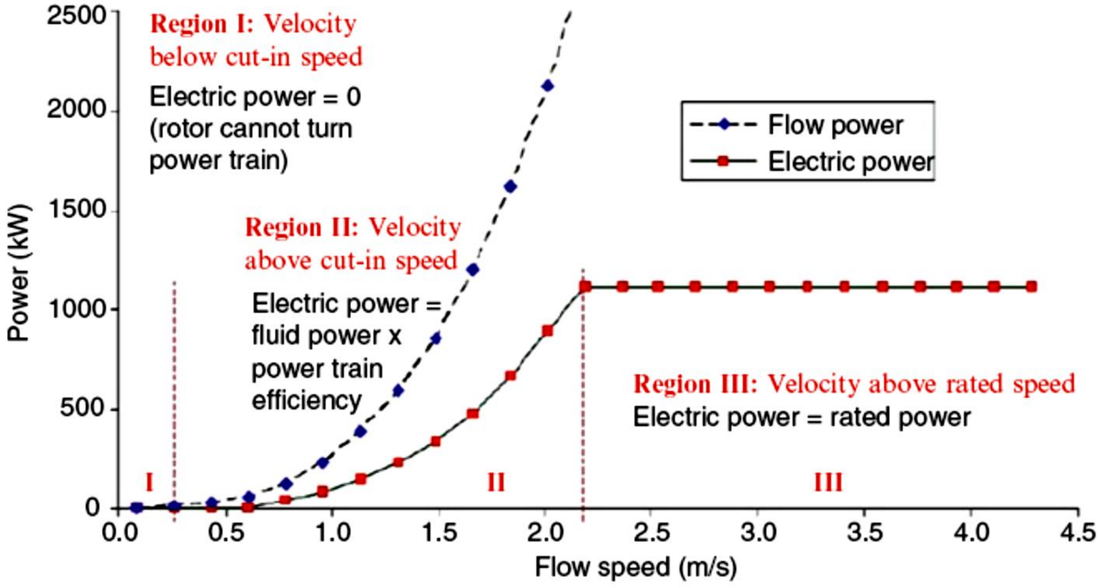
Slide#52- Turbomachinery Course- OCEAN ENERGY

Horizontal & Vertical Axis Turbines (HAT)

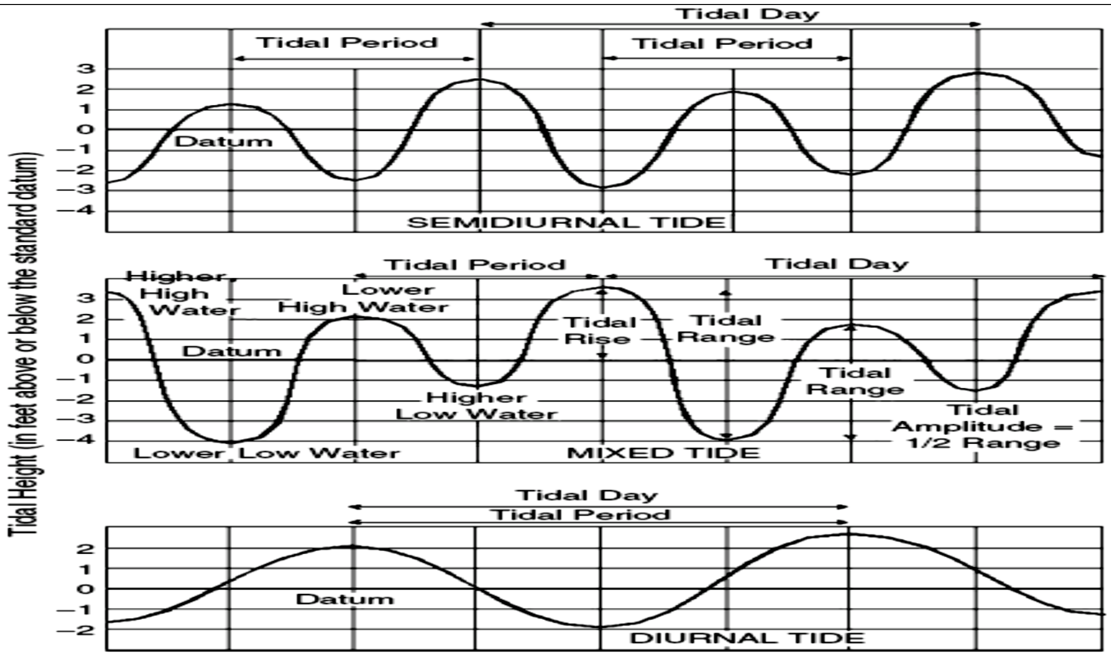




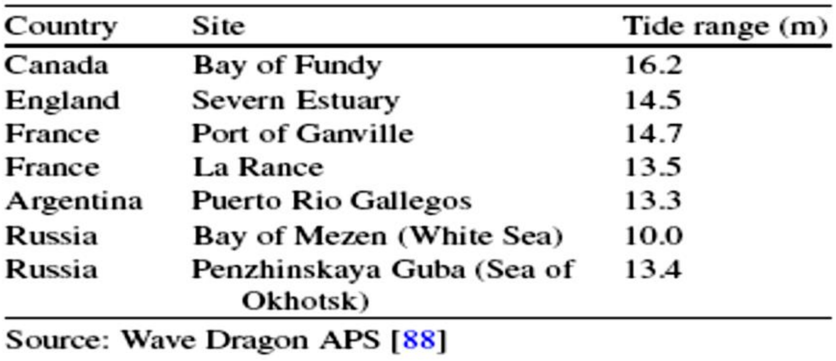

Extractable Power (kW)
2000
1750
1500
1250
1000
750
500
250
0
2
4
6
8
10
12
14
16
18
20
Rotor Diameter (m)
4 m/s
3 m/s
2 m/s
1 m/s
Expected Range


Power (kW)
2500
2000
1500
1000
500
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Flow speed (m/s)
Flow power
Electric power
Region I: Velocity below cut-in speed
Electric power = 0 (rotor cannot turn power train)
Region II: Velocity above cut-in speed
Electric power = fluid power x power train efficiency
Region III: Velocity above rated speed
Electric power = rated power
I
II
III

Different Types of Tides



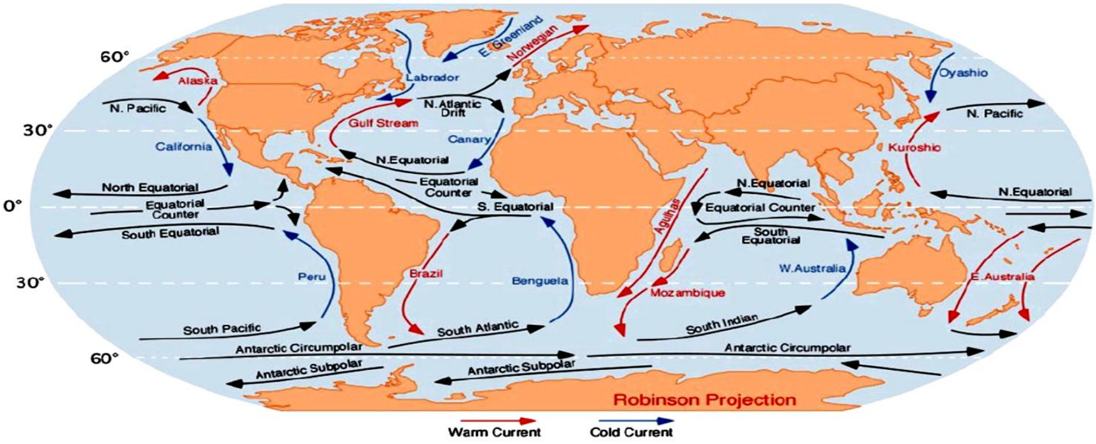
Locations for High Tides



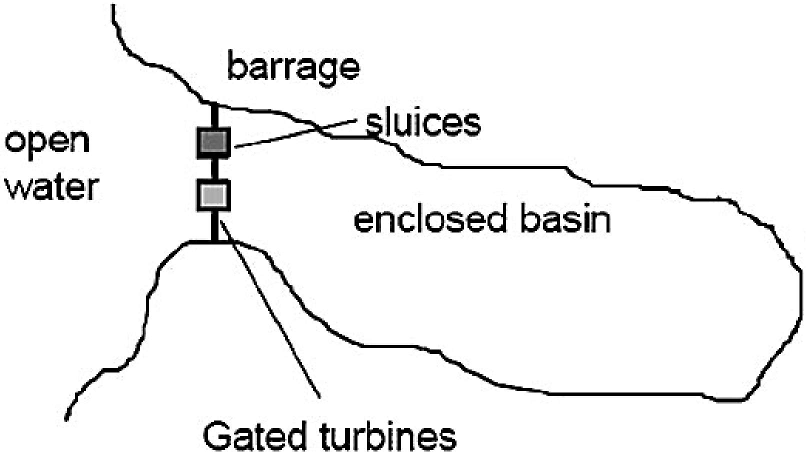
Country	Site	Tide range (m)
Canada	Bay of Fundy	16.2
England	Severn Estuary	14.5
France	Port of Ganville	14.7
France	La Rance	13.5
Argentina	Puerto Rio Gallegos	13.3
Russia	Bay of Mezen (White Sea)	10.0
Russia	Penzhinskaya Guba (Sea of Okhotsk)	13.4

Source: Wave Dragon APS [88]

Surface Ocean Current



Single-Basin Tidal Barrage Mode



Slide#56- Turbomachinery Course- OCEAN ENERGY (TIDAL)

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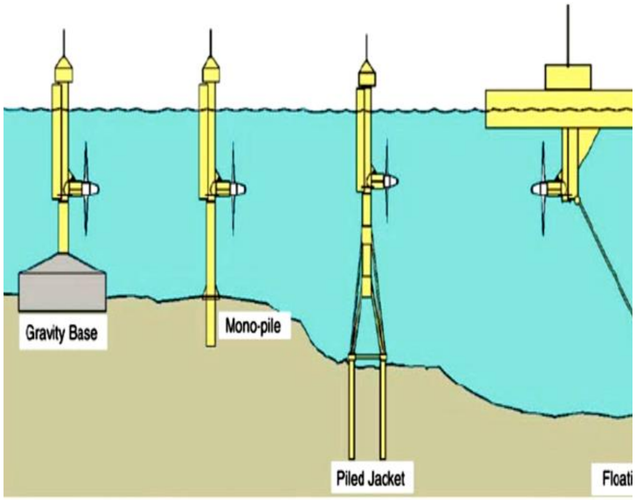
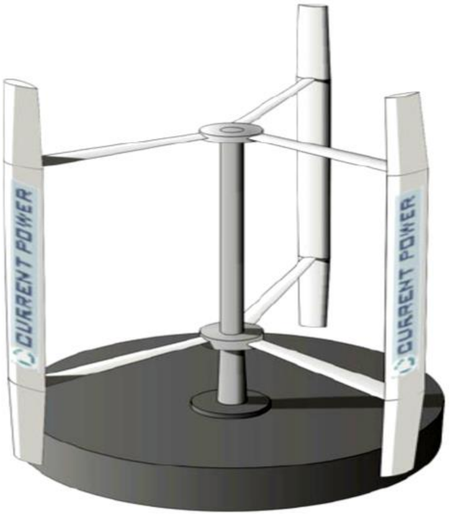
<td> </td>
<td> </td>
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Slide#57- Turbomachinery Course- GOROLOV TURBINE