CONTENT

I. PURPOSE

This manual can be used for preliminary selection, steam and cooling water planning for steam turbines in basic and detail engineering stages. This manual does not for designing steam turbine and the related parts.

II. STEAM TURBINE TYPES

Steam turbine types based on blade geometry and energy conversion process are impulse turbine and reaction turbine.

2.1. **Impulse Turbine**

Thermal energy of steam is converted to kinetic energy in turbine nozzle. Kinetic energy to be converted to blade become mechanical energy and transferred through rotor, shaft and coupling to the load. Enthalpy drop is high for each moving blades. See fig. 1. and fig. 2.

Impulse blade applies in Curtis and Rateau turbines such as the following typical

- Curtis turbine contain 1 row of nozzle for 2 row of impulse blades
- Rateau turbine contain 1 row of nozzle for 1 row of impulse blades, can be 1 pair up to several pair.
- 1 Curtis + Rateau rows constructed in one rotor.

2.2. **Reaction Turbine**

In reaction turbine, there is no nozzle to convert steam energy to mechanical energy. Moving blades work due to differential pressure of steam between front and at behind of moving blades. See fig. 1 and fig. 2.

In general, reaction turbine is not stand alone, but works at behind impulse turbine whether constructed in one rotor or at separated rotor, but still connected by coupling. The purpose of impulse turbine is to control speed and reduce steam enthalpy to specified level. Reaction turbine is just receiving steam condition from impulse blades. Typical pairs of reaction and impulse turbines are;

- 1 Curtis + Several rows of Rateau + Reaction rows
- 1 Rateau + Reaction rows
- Several rows of Rateau + Reaction rows

III. STEAM TURBINE OPERATING RANGE

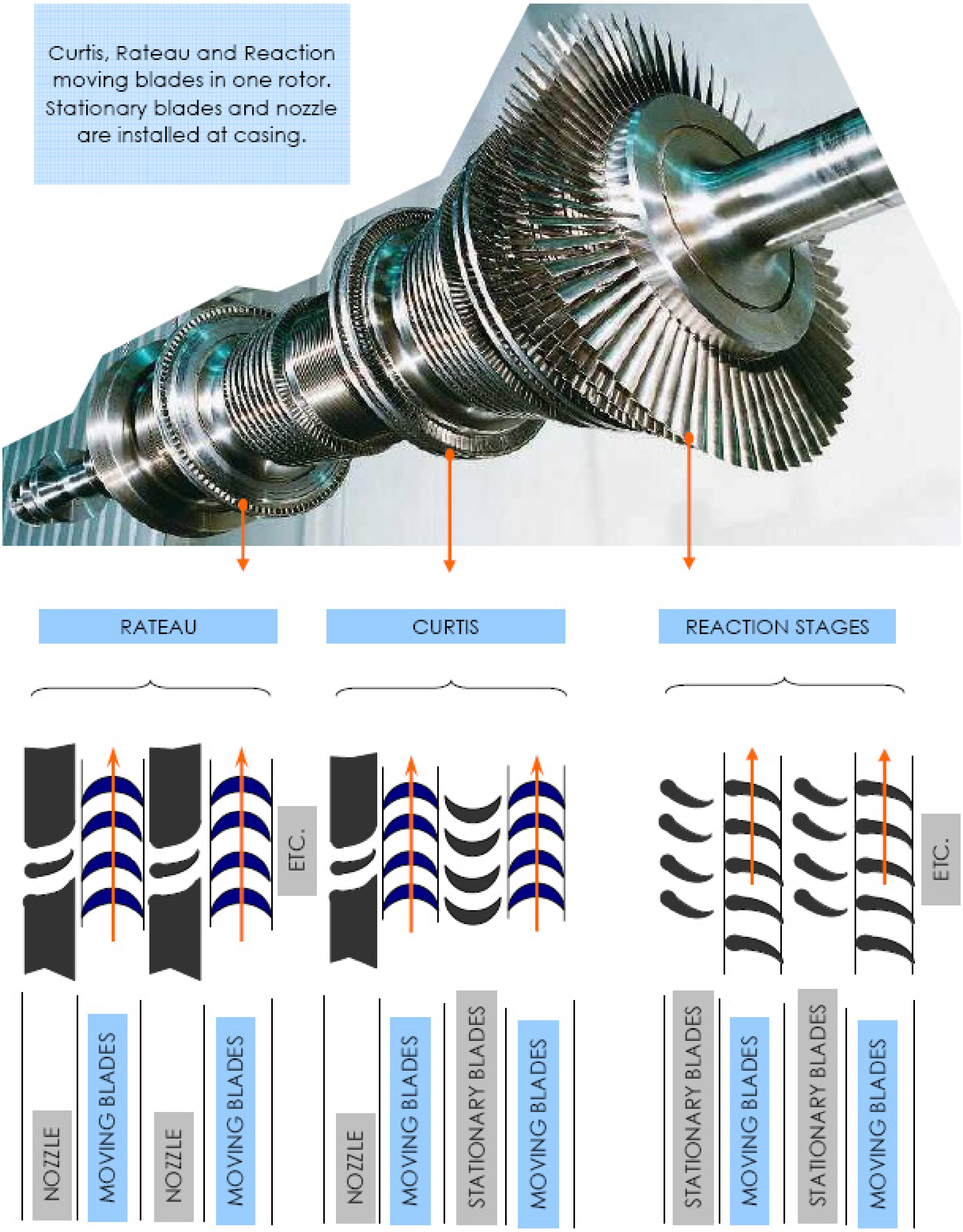
The following criteria are used for selection steam turbine type

3.1. Curtis (Stand alone or Single Stage)

a. Compact .
b. Power is relative small (up to 2000 kW).
c. Speed is relative low (up to 6000 rpm, except for special design up to 12000 rpm).
d. Enthalpy drop is high.

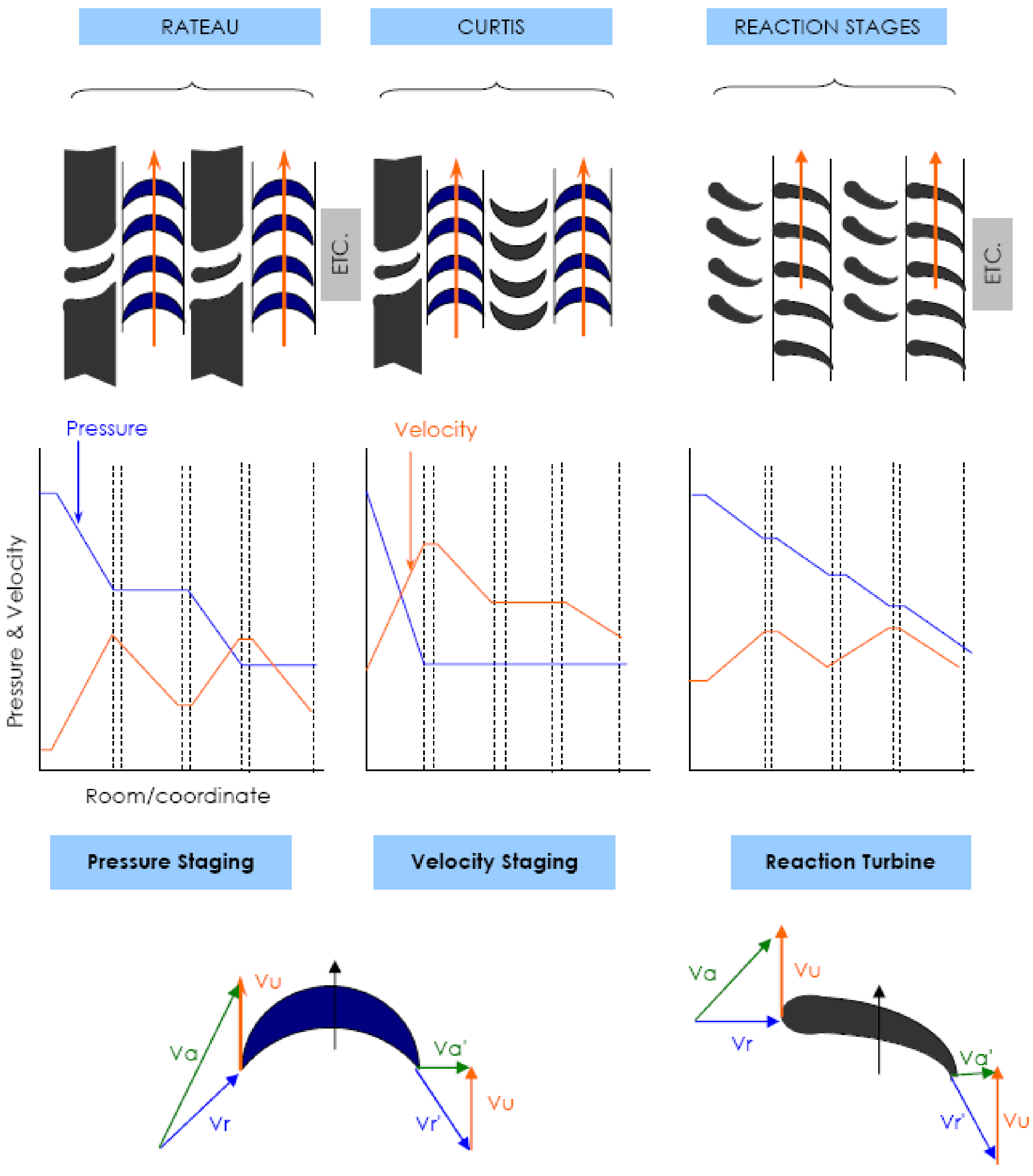
3.2. Rateau (Multi rows)

a. Efficiency is higher than Curtis
b. Power is high (up to 30,000 kW)
c. Generally, speed is higher than Curtis (up to15000 rpm)
d. Enthalpy drop for each row lower than Curtis but still high, higher than Reaction



Curtis, Rateau and Reaction moving blades in one rotor. Stationary blades and nozzle are installed at casing.

Figure 1. Steam turbine blades arrangement of Impulse and Reaction blades.



Steam kinetic energy converted to blades is :

$EK = (0.5\ m/g) \times (Va^2 - Va'^2)$

Figure 2. Pressure and velocity of steam across nozzle and blades in impulse and reaction blades

3.3 <u>Reaction (Multi row reaction + 1 row impulse for control stage)</u>

a. More efficient
b. Power is high
c. Speed is high (up to15000 rpm)
d. Enthalpy drop each row is low
e. For low steam pressure.

Operating range of steam turbines can be shown in Speed – Power chart such as the following figure (Fig. 3)

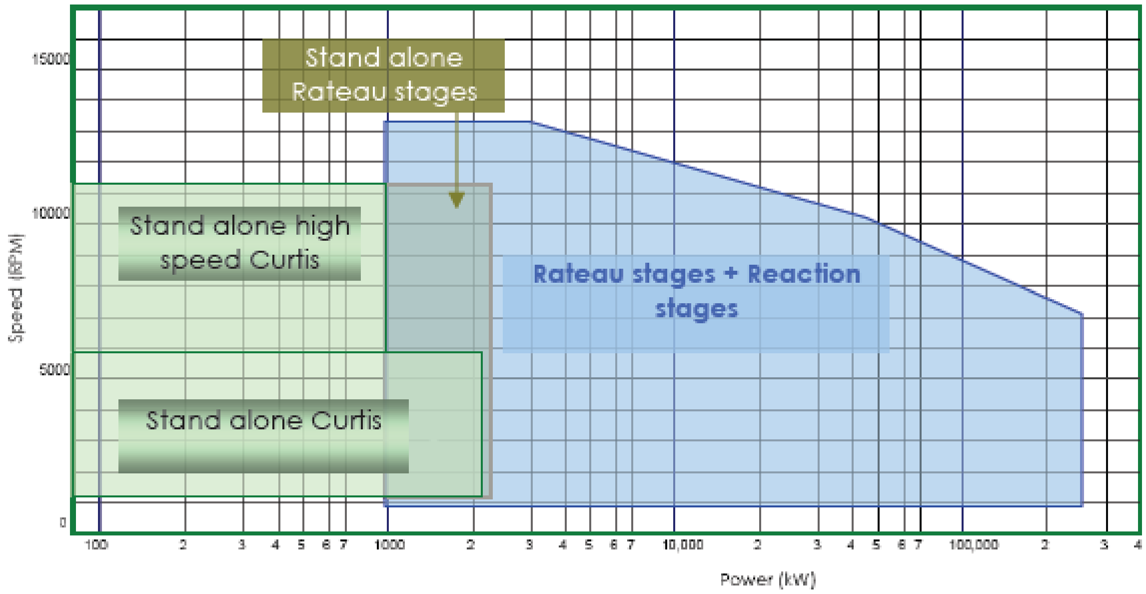


Figure 3. Operating Range of Steam Turbines

IV. SYMBOLS AND UNITS

Unless otherwise noted, the following symbols and units are used in this manual.

Symbol	Description	Unit
Power and speed		
P	Power	kW (kilowatt)
N	Speed	RPM (rotary per minute)
Blade and rotor geometry		
D	Rotor diameter	mm
U	Peripheral velocity	m/s
l	Blade height	mm
S	Blade length	mm
λ	S/l ratio	
D/l	D/l ratio	
Z	Number of row or number of stage	
Factors, coefficient and efficiency		
Vrat	Velocity ratio (= U / C)	
C	Steam velocity = $44.7 \sqrt{\Delta h}$	m/s
μs	Head coefficient (= $1000 \Delta h / U^2$)	
ε	Degrees of admission	
F_l	Efficiency factor due to blade height	
$F\varepsilon$	Efficiency factor due to degrees of admission	
η	Efficiency non percent for calculation	

Steam condition

pi	Steam inlet pressure to turbine	bar A
pi ‘	Governor valve exhaust pressure	bar A
po	Steam exhaust pressure	bar A
ti	Steam inlet temperature	^{0}C
ti ‘	Gov. valve exhaust temperature	^{0}C
vi ‘	Gov. valve exhaust specific volume	m^3 / kg
vo	Specific volume leaving last blade	m^3 / kg
hi	Inlet enthalpy	kJ/kg
hos	Enthalpy in isentropic process from pi condition to po condition	kJ/kg
hos’	Enthalpy in isentropic process from pi’ (leaving governor valve) condition to po condition	kJ/kg
he	Turbine diff. enthalpy	kJ/kg
Δhs	Isentropic diff. enthalpy (= hi – hes)	kJ/kg
Δhs’	Isentropic diff. enthalpy from pi’ to po (= hi – hes’)	kJ/kg
Δhs1-etc.	Isentropic diff. enthalpy of row	kJ/kg
Δhstg	Average Isentropic diff. enthalpy of stages	kJ/kg
Δhe	Turbine head (turbine enthalpy)	kJ/kg
Δhe’	Effective turbine head	kJ/kg
x	Wetness of steam	
m	Mass flow	ton/hr

Subscript

If there is subscript follows the symbol, meaning as

IMP	Impulse or control stage
R	Reaction
RAT	Rateau
CUR	Curtis
STG	Average of stages or each row
Loss	Losses
m	Mechanical
tip	Tip (for tip speed of blade)
25	At 25 mm of nozzle height and 0.25 of degrees of admission for impulse turbine
05	At equal or more than 80 mm of nozzle height and more than 0.5 of degrees of admission for impulse turbine
10	At D/l = 10 and S/l = 0.4 for reaction turbine
1..n	At first to n of stage or row
z	At last stage or last row
I, II, etc.	Alternative number
o	Output, exhaust, exit

V. STEAM PROCESS IN STEAM TURBINE

Steam entrance to turbine through governor valve to control steam capacity and therefore to control turbine speed. There is enthalpy loss at this valve. Following figures show steam process in steam turbine.

Figure 4 shows steam process in enthalpy against entropy diagram of Curtis and single row Rateau turbine. Figure 5 shows steam process of multi row of Rateau turbine. And figure 6 shows steam process of impulse as control stage and reaction turbine.

VI. EXHAUST STEAM CONDITIONS, EXTRACTION AND ADMISSION

6.1. Back Pressure and Condensing Turbine.

The name "Condensing turbine" and "Back pressure turbine" expressed about steam condition exit the turbines. If steam condition exit the turbine in wet steam or where steam condition at bellow saturated line of Mollier diagram, named condensing turbine. If steam condition exit the turbine in dry or still in superheated condition or at upper of saturated line of Mollier diagram, named back pressure turbine, see figure 7.

6.2. Steam Extraction and Admission of Turbine

In applications, when required, steam can be extracted from turbine before steam flowing through the last stage, named extraction turbine. In the other case, if required, steam also can be admitted to turbine before last stage, named admission turbine, see figure 8.

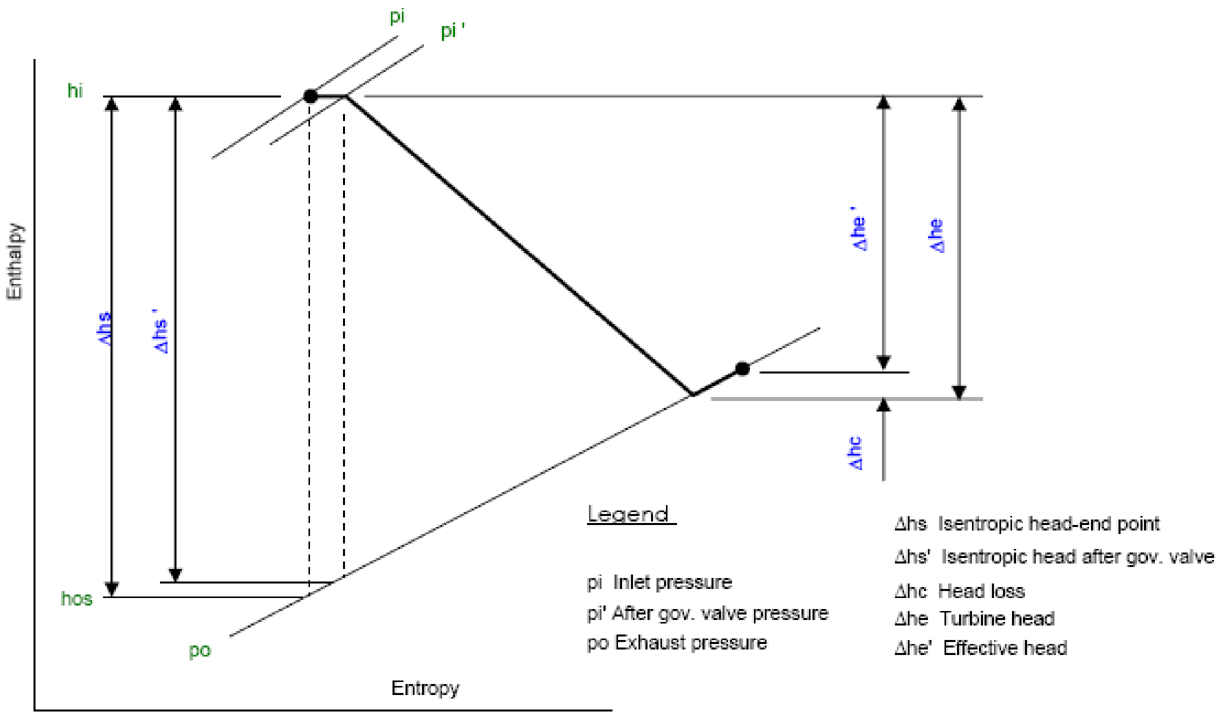
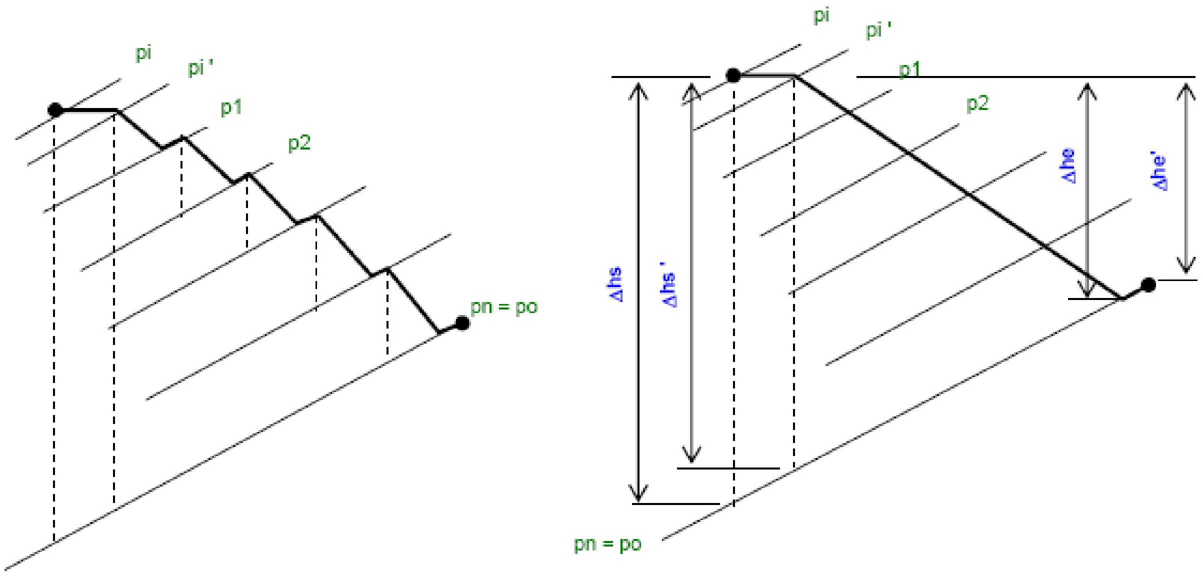


Figure 4 Steam Process in Curtis and Single Row Rateau Turbine

Typical steam admission and extraction arrangement

- 1 Curtis atau Rateau rows + ***Extraction/Admission*** + Reaction rows
- 1 Curtis + ***Extraction/Admission*** + 1 Rateau + Reaction rows
- 1 Curtis + ***Extraction/Admission*** + Rateau rows



Detailed diagram

Simplified diagram

Figure 5. Steam Process in Multi Row of Rateau Turbine

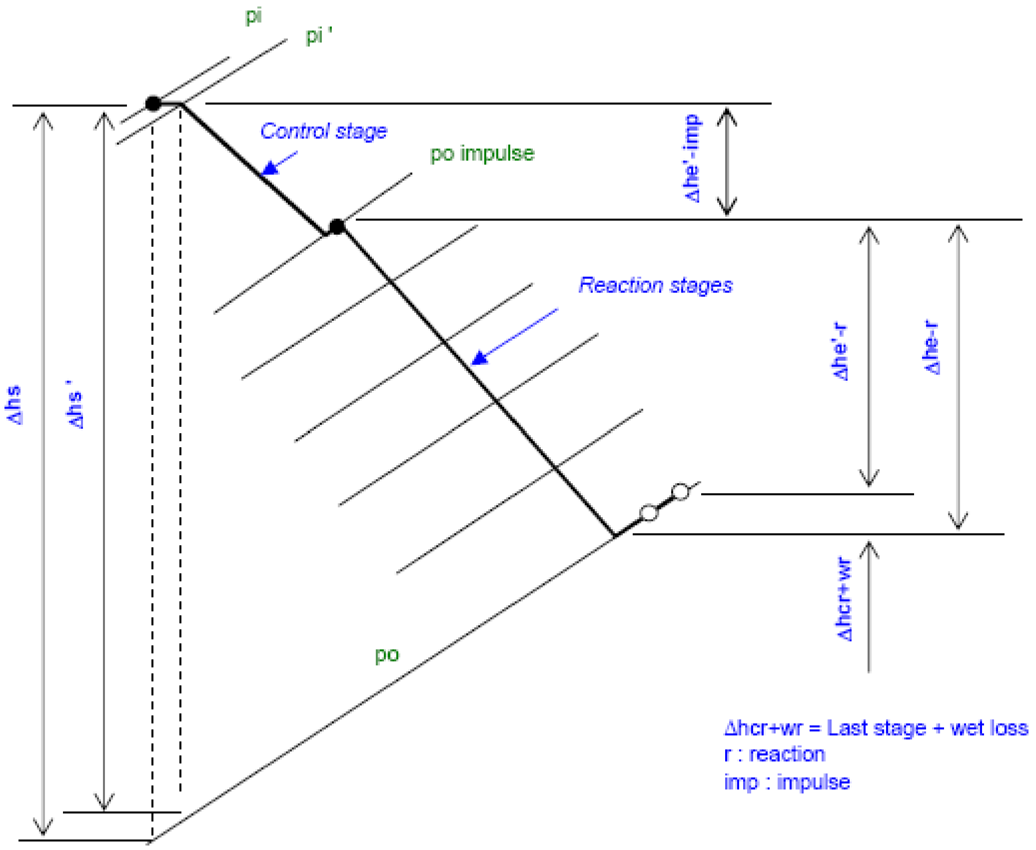


Figure 6. Steam Process in Impulse as Control Stage and Reaction Turbine

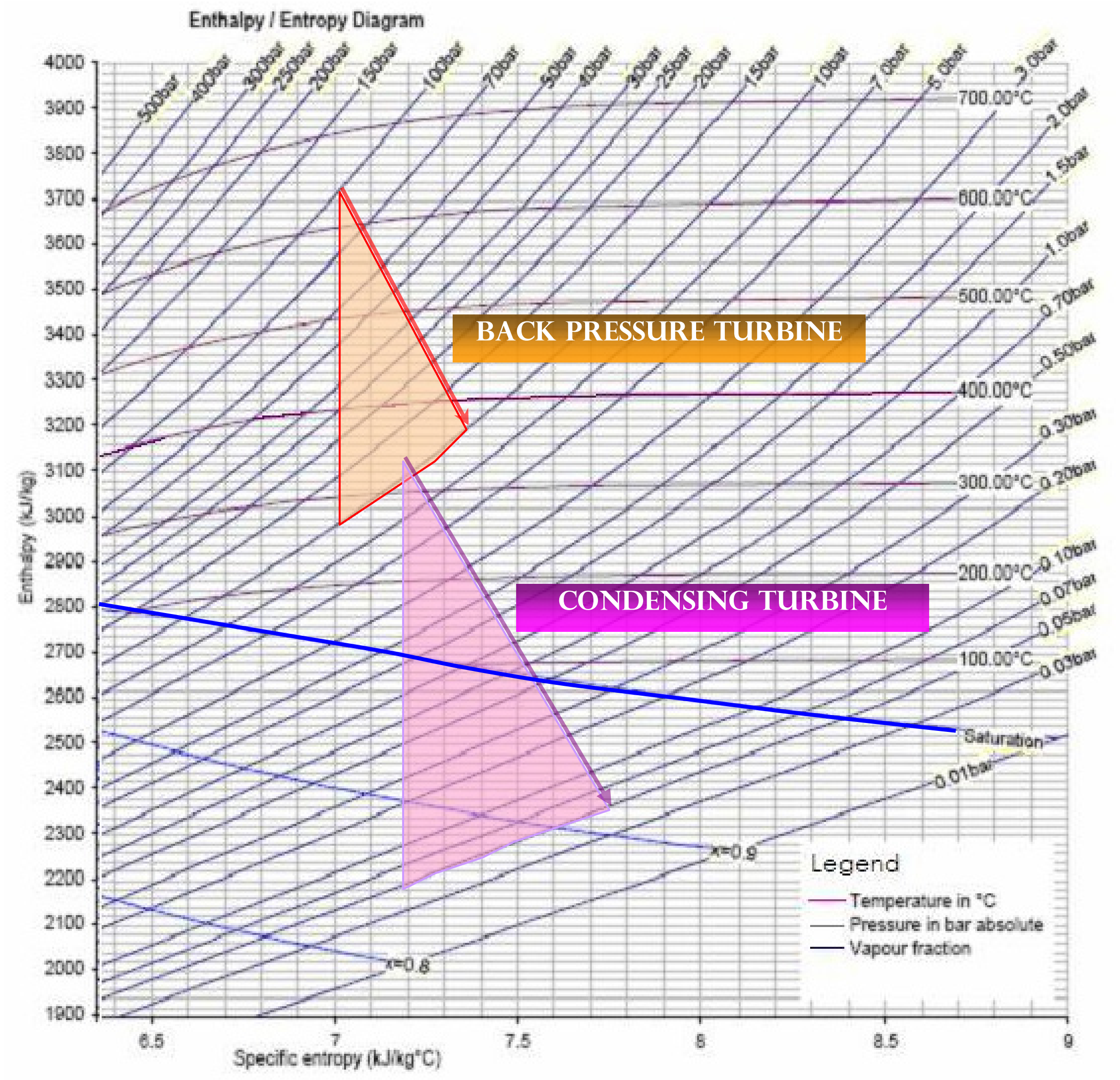


Figure 7. Back Pressure and Condensing Turbine

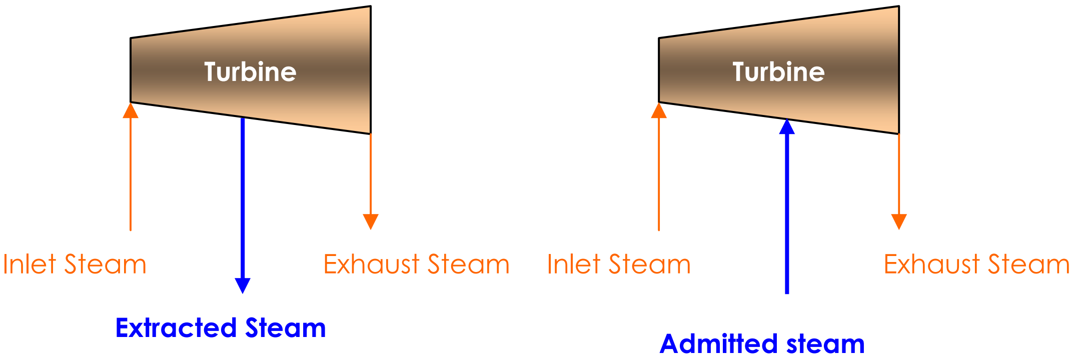


Figure 8. Extraction and Admission Steam Turbine

VII. STEAM CONSUMPTION

Steam consumption of steam turbine is depending to required output power and efficiency of the turbine. Efficiency will depend on turbine size or rotor diameter, blade geometries, speed, extreme condition of steam and other losses.

7.1. Rotor diameter

Turbine Manufacturers have nominal rotor diameter for their products. Each size has specific operating range even sometimes operating point required by Customer does not at highest efficiency. Nominal size is required by Manufacturer because of competitive cost reasons. Typical model and size are shown in figure 9, 10 and 11.

7.2. Steam Temperature.

Very high steam temperature will decrease strength of material of turbine blades and cause limitation of design speed. Lower speed and high enthalpy differential will reduce efficiency of turbine, see red dot line at figure 9, 10 and 11.

7.3. Blade size, speed and degrees of admission.

Blade type, size, degrees of admission and speed are influence to turbine efficiency, see figure 13 for impulse turbine and figure 14 for reaction turbine.

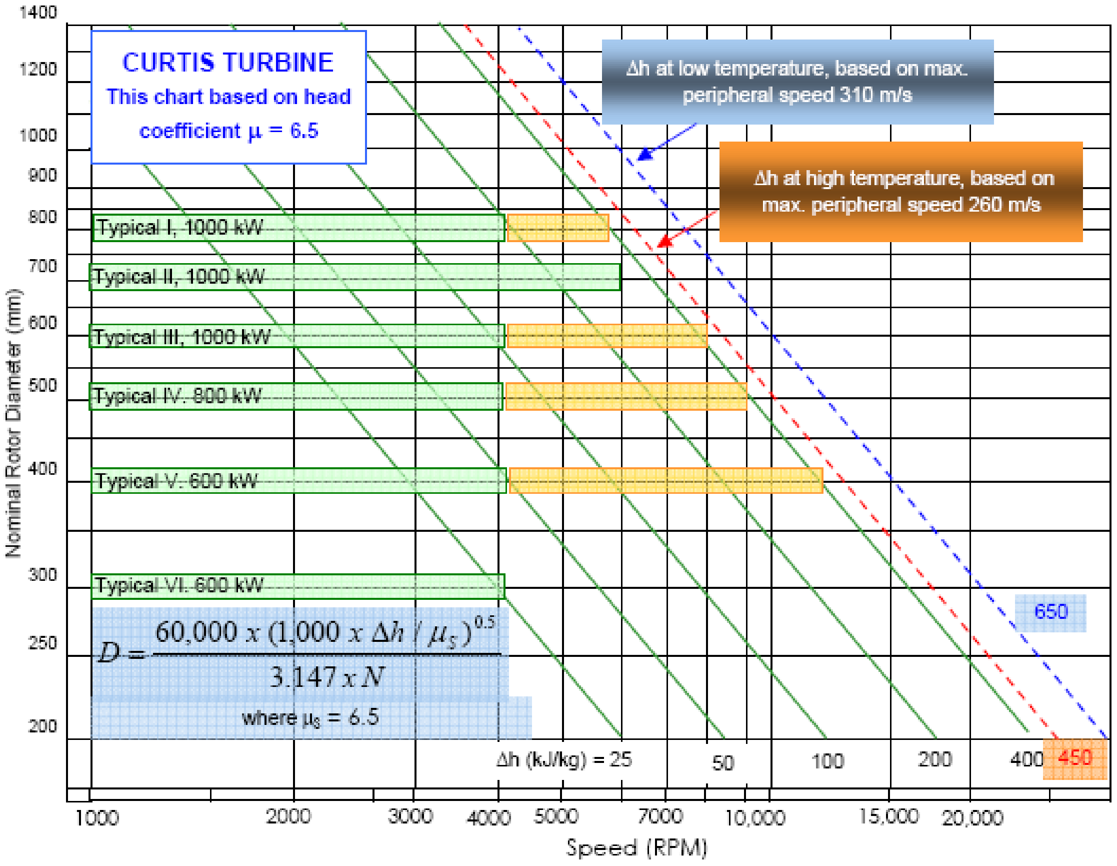


Figure 9. Output power, speed and enthalpy range for several design of Curtis Turbine

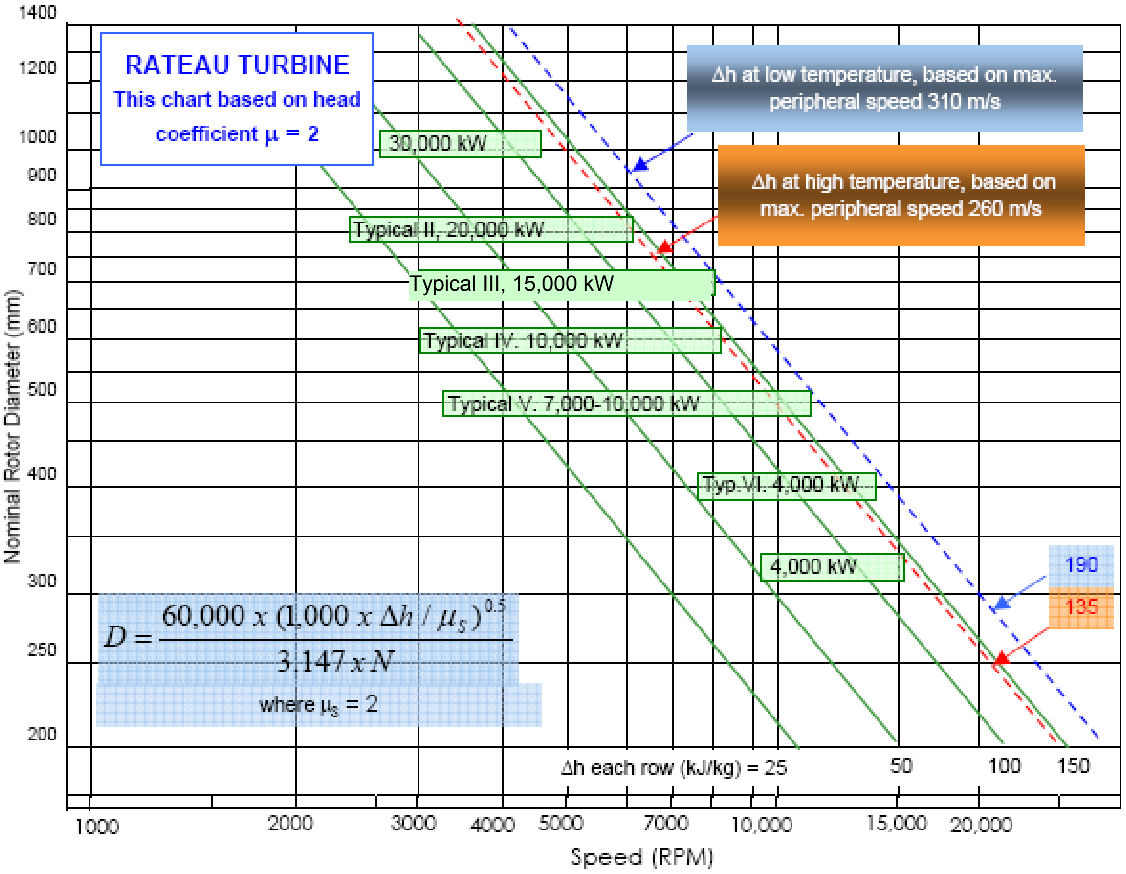


Figure 10. Output power, speed and enthalpy range for several design of Rateau Turbine

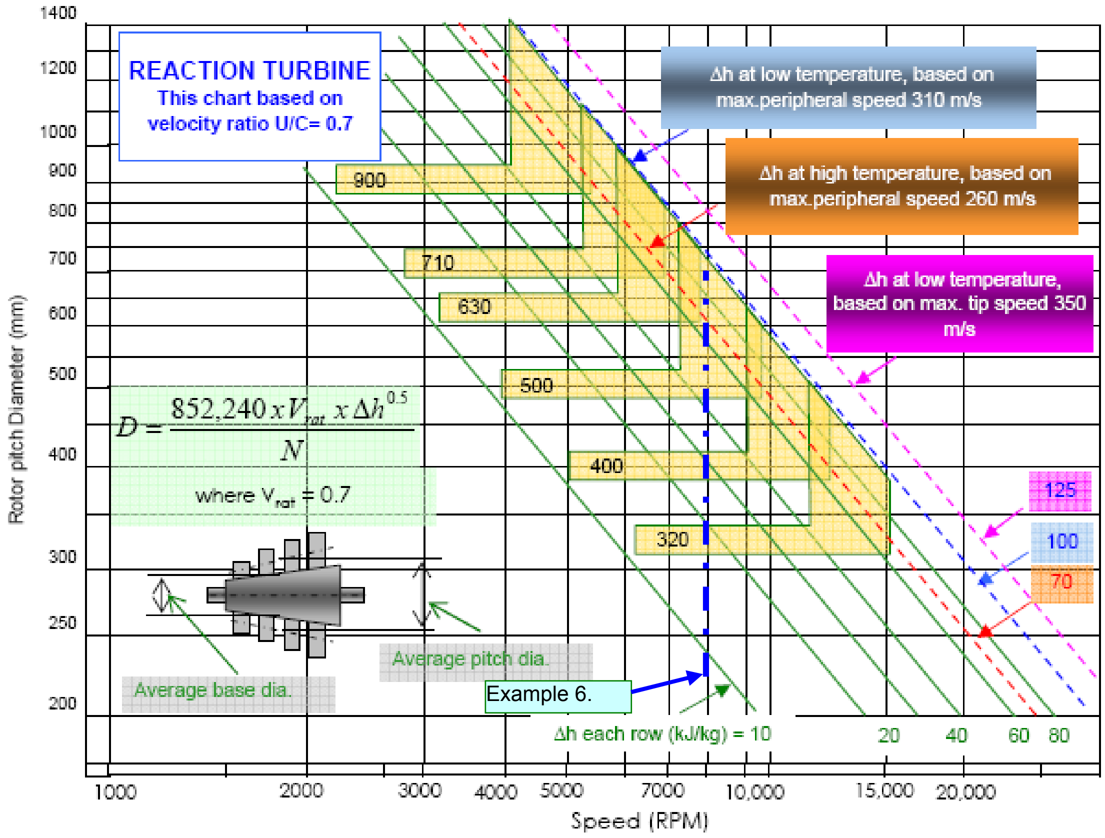


Figure 11. Output power, speed and enthalpy range for several design of Reaction Turbine

Interpretation examples of figure 9, figure 10 and figure 11.

Curtis turbine,

Example 1. Given Δh = 100 kJ/kg for Curtis turbine that shall operate for pump at 750 kW and 2975 RPM without reducing gear. Figure 9 shows that at 750 kW , 2975 RPM and Δh = 100 kJ/kg the nearest size is typical I and II where designed for 1000 kW. This typical is sufficient even if the size is bigger than required.

Example 2. Available steam is Δh = 150 kJ/kg for turbine that shall give 400 kW of power and 2975 RPM for centrifugal pump. Reducing gear is acceptable. Figure 9 shows that typical no. V at 7,200 RPM is the best choice. Gear is necessary for reducing speed from 7,200 RPM to 2975 RPM.

Example 3. Available steam is Δh = 600 kJ/kg, 100 bar A and 650 °C for Curtis turbine. Turbine shall operate at 900 kW and at any speed. Figure 9 shows that no typical design is available for this requirement. To provide best efficiency, turbine shall be operated at speed higher than limited speed indicated by red dot line for high temperature. Typical no. I may be acceptable but does not at best efficiency.

Rateau turbine,

Example 4. Available steam is equal to example 3 above but for 5,000 kW of Rateau turbine. From figure 10 shows that for 5,000 kW, typical no. V is the nearest to requirement point. Turbine can be operated at 8,000 RPM and Δh_{STG} = 100 kJ/kg. Turbine has number of stages for approximately of 600/100 = 6 stages.

Example 5. Available steam is Δh = 650 kJ/kg, 110 bar A, 700 °C for 15,000 kW and at any speed. Figure 10 shows that typical no. III is the nearest to requirement point. Turbine can be operated at 8,000 RPM and Δh_{STG} = 135 kJ/kg. Number of stage is approximately = 650/135 = 5 stages.

Reaction turbine,

Example 6. Reaction turbine shall be used in the downstream of control stage that has been designed at 8,000 RPM of operating speed. Steam available for reaction turbine is Δh_R = 400 kJ/kg and inlet temperature at 250 C. Figure 11 shows that at 8,000 RPM vertical line will cross blue dot line and red dot line at diameter of rotor is at 500 mm area. This line cross with red dot line (Δh_{STG} = 70 kJ/kg) at 600 mm pitch diameter and cross with blue dot line (Δh_{STG} = 100 kJ/kg) at 700 mm of pitch diameter.
The diameter of 500 mm listed in this area is rotor base diameter. Therefore, in this example, approximately average base diameter is 500 mm and approximately average pitch diameter is 600 mm for high temperature or 700 mm for low temperature. Number of stages is = 400/100 = 4 for low temperature and = 400/70 = 6 for high temperature.

Interpretation examples of figure 12, 13 and 14

Example 7. Rateau turbine has blade height, l = 30 mm, Δh=200 kJ/kg, U=250 m/s and ε = 0.2. From equation (4) in chapter VIII, determine $\mu_S = 1{,}000 \times \Delta h / U^2$ = 3.2 and then from figure 12 can be read efficiency for $l \geq 80$ mm and $\varepsilon \geq 0.5$, η_{05} = 77.5 %. From figure 13 at l = 30 mm, factor due to nozzle height F_l is 0.955 and by equation, F_ε = 0.96. Turbine efficiency than become η_{IMP} = 77.5 x 0.955 x 0.96 = 71 % or 0.71.

Example 8. Reaction turbine has Vrat = 0.65, S/l = 0.4 and D/l = 8. Efficiency of turbine can be determined from figure 14. Following the red lines, efficiency η_R= 87.2 % or 0.872

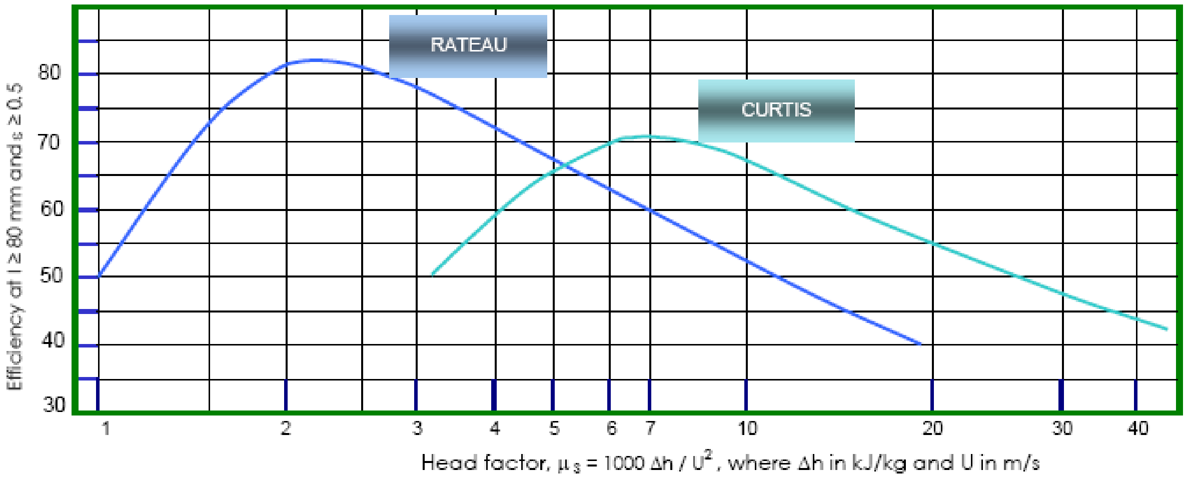
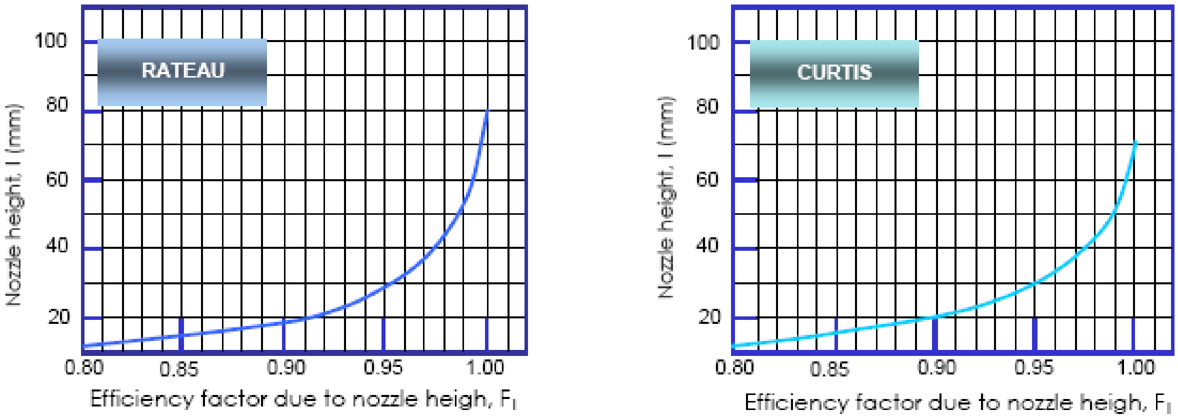


Figure 12. Efficiency of Impulse Turbine (η_{05})at $l \geq 80$ mm and $\varepsilon \geq 0.5$



Efficiency factor due to degrees of admission

Rateau , $Fe = 0.8823653 + 0.3955798\ \varepsilon - 0.3286096\ \varepsilon^2$. If $\varepsilon > 0.5$, $Fe = 1$

Curtis , $Fe = 0.7811724 + 0.6089226\ \varepsilon - 0.3511378\ \varepsilon^2$. If $\varepsilon > 0.5$, $Fe = 1$

where ε : degrees of admission = Projection Area of Nozzle / Total area of moving blades

for *reaction* turbine, $\varepsilon = 1$

Figure 13. Efficiency Factor Due To Nozzle Height and Due To Degrees of admission

7.4. Other Losses

Other losses which reduce total turbine efficiency are:

- Peripheral losses at impulse blades.
- Wetness loss at reaction blades.
- Mechanical losses, see figure 15.
- Enthalpy drop at governor valve.

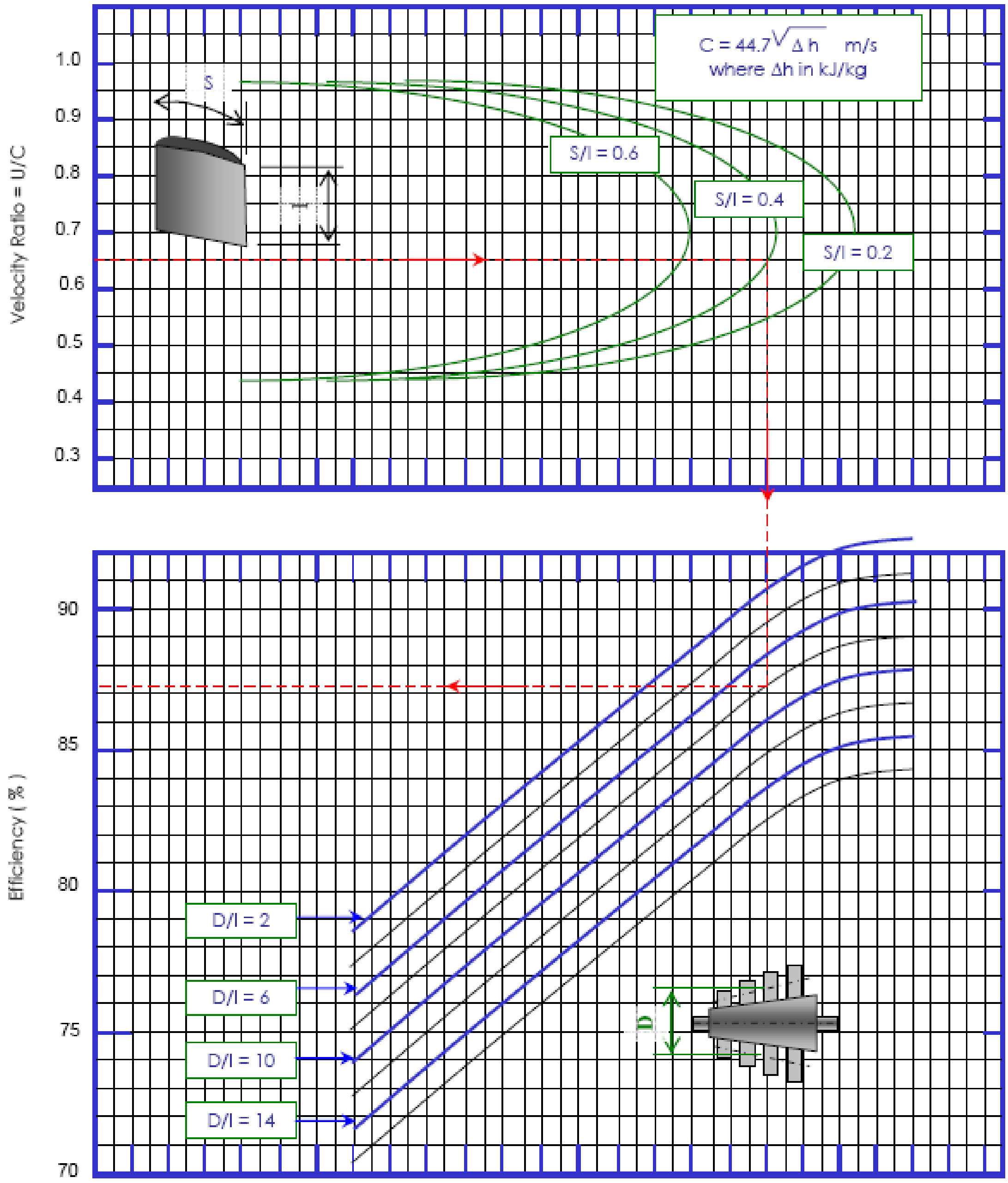


Figure 14. Efficiency of Reaction Turbine

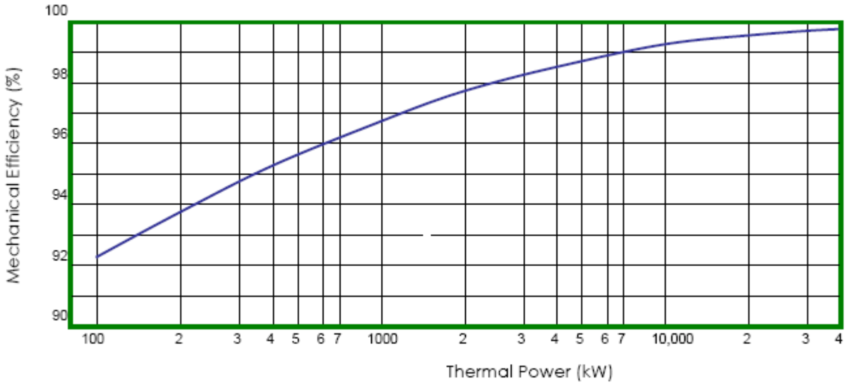


Figure 15. Mechanical Efficiency

VIII. CALCULATION FORMULA

All following formulas shall be used with unit where presented in chapter IV to minimize an error during calculation caused by inconsistence units. If there is following calculation symbols, mening: "+" : plus, "-" : minus, "x" multiply, "/" divided by, "=" : equal to, subscript : power.

Peripheral velocity, $U = \dfrac{3.147 x D x N}{60,000}$ (m/s) (1)

Steam velocity, $C = 44.7 \text{ x } (\Delta h)^{0.5}$ (m/s) (2)

Velocity ratio, $Vrat = U / C$ (3)

Head coefficient, $\mu_S = \dfrac{1,000 x \Delta h}{U^2}$ (4)

Peripheral power losses,

$P_{LOSS} = \{25 \text{ x } D \text{ x } 10^{-5} + 0.05 \text{ x } l \text{ x } (1-\varepsilon)\} \text{ x } (D \text{ x } U^3 \text{ x } 10^{-9}) / vo$ (kW) (5)

Total efficiency, $\eta_{TOTAL} = \eta_{TUR} \text{ x } \eta_{WET} \text{ x } \eta_m$ (6)

Wetness efficiency, $\eta_{WET} = 1 - 0.5 \text{ x } (1-X_O) \text{ x } \Delta h_{WET} / \Delta hs'$ (7)

= 1 when at superheated

Mechanical efficiency (η_m), see figure 15

Turbine efficiency, $\eta_{TUR} = \dfrac{3.6 x P}{m \text{ } x \Delta hs'}$ (8)

Steam mass flow, $m = \dfrac{3.6 \text{ } x \text{ } (P + P_{LOSS})}{\eta_{TOTAL} \text{ } x \text{ } \Delta hs'}$ (ton/hr) (9)

Outlet losses for reaction turbine,

$\Delta he = C_O^2 / 2000$ (kJ/kg) (10)

Losses at governor valve, $\Delta hs' = 0.93 \text{ x } \Delta hs$ for single gov. valve (kJ/kg) (11)
$= 0.97 \text{ x } \Delta hs$ for multi gov. valve

Number of stages of Impulse or Rateau stages,

$Z_I = \dfrac{1.55 \text{ } x \text{ } \Delta hs'_{RAT} \text{ } x \text{ } 10^{11}}{D^2 \text{ } x \text{ } N^2}$ (integer value) (12)

$z_{II} \geq 2 \text{ x } [\log(po / pi')]_{ABS}$ (integer value)

(for convergen nozzle, pressure ratio shall ≥ 0.3 for each row)

Number of stages of reaction turbine,

$$Z_R = \frac{3.8\ x\ \Delta hs'_R\ x\ 10^{11}}{D^2\ x\ N^2} \quad \text{(integer value)} \qquad (12a)$$

Differential enthalpy of each stage,

$$\Delta h_{STG} = \Delta hs'_{RAT} / z \quad \text{for Rateau turbine (kJ/kg)} \qquad (13)$$

$$\Delta h_{STG} = \Delta hs'_R / z \quad \text{for reaction turbine}$$

Turbine power of each stage, $P_{STG} = P / z$ (14)

Nozzle height x degrees of admission,

$$l \times \varepsilon = \frac{P_{STG}\ x\ vi'\ x\ 10^6}{D\ x\ A\ x \eta\ x \Delta h_{stg}^{1.5}} \quad \text{(mm)} \qquad (15)$$

For single stage, $P_{STG} = P$ and $\Delta h_{STG} = \Delta hs'$
For impulse turbine, $\varepsilon = 0.015$ up to 0.45 for welded nozzle
ε_{MAX} is about 0.9
$\varepsilon_{MIN} = 0.007$ for reaming nozzle
$\varepsilon = 1$ for reaction turbine
A is nozzle area factor or entrance area factor = $3.147 \times 44.7 \times \sin \alpha$

$A = 34$ if $vi' < 0.1\ m^3 / kg$
$= 39$ if $0.1 \le vi' \le 1\ m^3/kg$
$= 43$ if $vi' > 1\ m^3/kg$

Impulse blades efficiency, $\eta_{IMP} = \eta_{05} \times F_l \times F_\varepsilon$ (16)
See figure 12 for η_{05} and figure 13 for F_l and F_ε

Reaction blades efficiency (η_R) can be determined with figure 14.

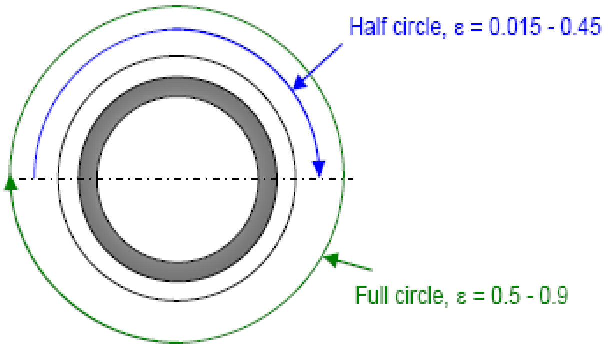


Figure 16. Welded Nozzle Degree of Admission of Rateau Turbine

IX. CALCULATION SHEET

Calculation sheet is necessary to make a simple, structured and documented of the calculation. Typical calculation sheets presented in attachments of this manual are divided into two categories where is depending on the requirements.

a. To calculate steam flow where power and/or speed is as required condition
b. To calculate power output where quantity and condition of steam is known

All required variables for calculation are taken from formulas and charts presented in this manual and the attachments. Attachment A presents steam data in tables and charts for saturated and superheated conditions where taken from internet with some little modification on appearance.

Calculation sheets are presented in attachment B for stand alone impulse turbines, impulse and reaction turbines, admission steam turbine, extraction, admitted and extracted turbine.

X. UNIT CONVERSION

Designation	Unit to be converted	Factor	Unit to be used
Length	ft	304.8	mm
	inch	25.4	mm
Pressure	psi	0.06897	bar
	kg/cm^2 (at.)	0.981	bar
	atm.	1.013	bar
	Pa (Pascal)	10^{-5}	bar
Temperature	F (Fahrenheit)	(t-32) x (5/9)	C
	K (Kelvin)	T - 273	C
	R (Rankin)	(5/9)	K
Velocity	ft/s	0.3048	m/s
	ft/min (fpm)	0.00508	m/s
Volume flow	GPM (US)	0.227	m^3/hr
	CFM	1.699	m^3/hr
Mass	lb	0.4536	kg
Power	HP	0.7457	kW
Head	ft	0.3048	m
Enthalpy	kcal/kg	4.1868	kJ/kg
	BTU/lb	2.326	kJ/kg
Gas constant	kcal/kg.K	4.1868	kJ/kg.K
Specific heat & Entropy	BTU/lb.R	4.1868	kJ/kg.K
Specific mass or density	lb/ft^3	16.0185	kg/m^3
Specific volume	ft^3 /lb	0.06243	m^3/kg
Viscosity	$N.s/m^2$	1000	cP
	$lbf.s/ft^2$	47880.3	cP

Note : American Standard State condition is condition where pressure at 1.013 bar A and temperature at 15.5 C. In volume, is common written as SCF. Normal condition is at 1.0132 bar A and 0 C. In volume, is common written as Nm^3