CHAPTER (14)

TURBOMACHINARY

SUMMARY

Dr. MUNZER EBAID

Types of Fluid Machines

1. Positive Displacement Machines.

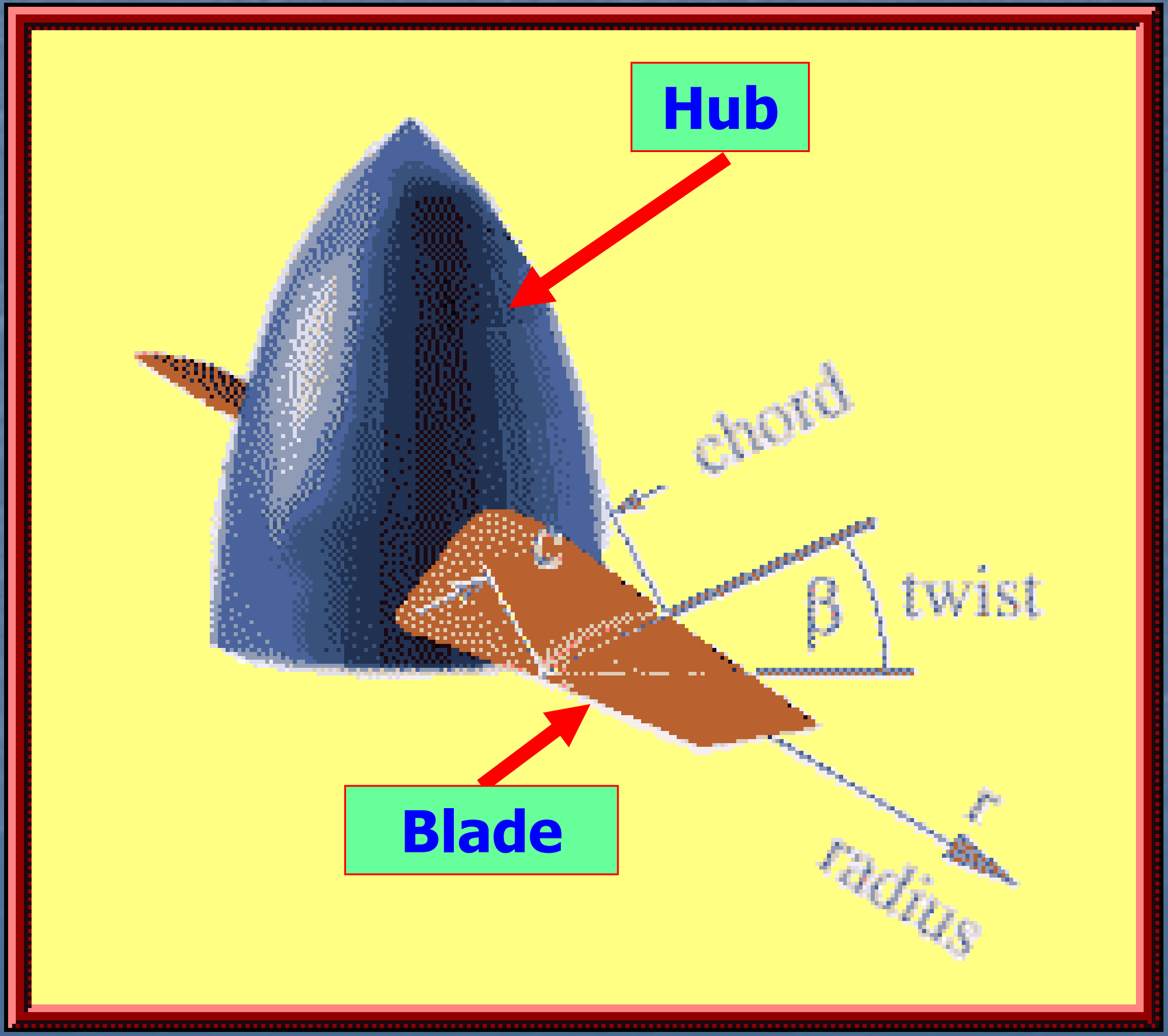
They operates by forcing fluid into or out of a chamber. Ex. (Automotive Engines, Gear Pumps)

2. Turbo-Machines.

They involve the flow of fluid through rotating blades or rotors that **Added Energy to the fluid,** (Ex. Pumps (Liquids), Fan, blowers and compressors (Gases).

OR Remove Energy from the fluid. (Ex. Wind turbines, Gas turbines and Hydraulic turbines)

PROPELLER



Thrust (T) of a propeller is a function of:

$$T = f(D, \omega, V_0, \rho, \mu) \qquad (14.3)$$

Performing a dimensional analysis using the methods presented in Chapter 8, we find

$$\frac{T}{\rho n^2 D^4} = f\left(\frac{V_0}{nD}, \frac{\rho D^2 n}{\mu}\right) \qquad (14.4)$$

n=revolution per seconds

Thrust Coefficient — $\frac{T}{\rho n^2 D^4}$

Advance Ratio — $\frac{V_0}{nD}$

Reynolds Number — $\frac{\rho D^2 n}{\mu}$

$$Thrust(T) = C_T\left(\rho n^2 D^4\right)$$

$$C_T = f\left(\frac{V_0}{nD}\right)$$

Power (P) of a propeller

$$Power = P = C_P\left(\rho n^3 D^5\right)$$

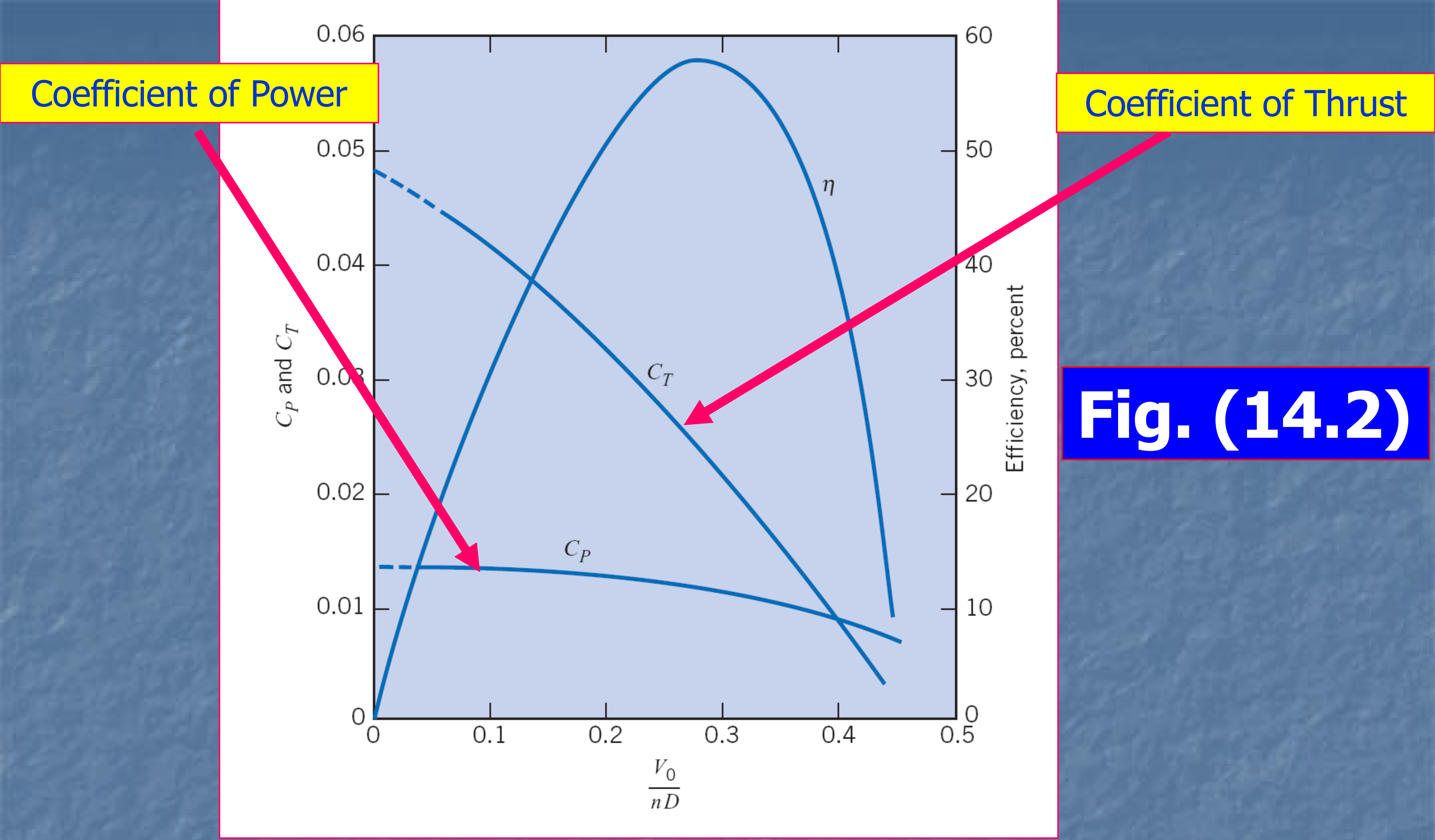
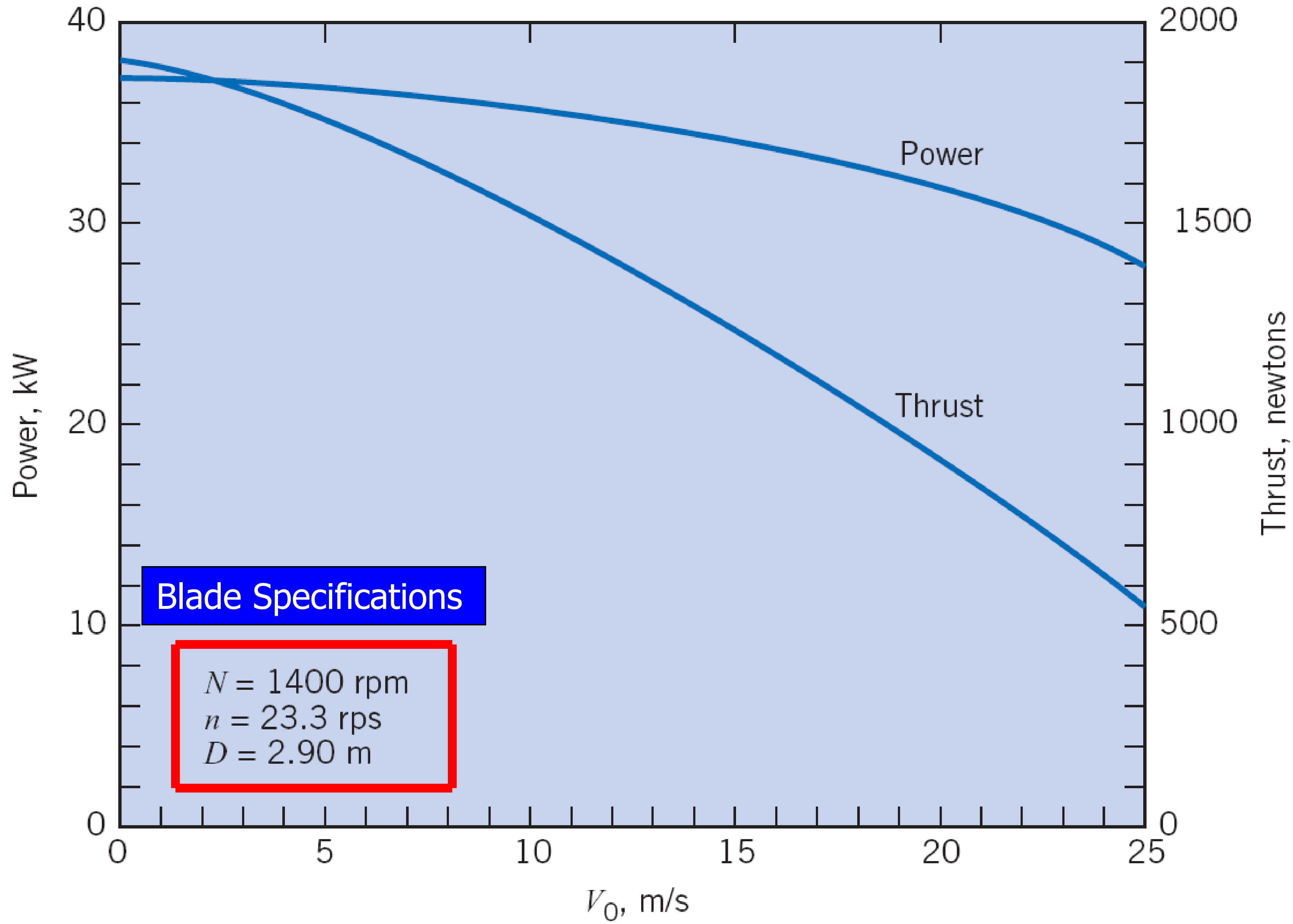


Fig. (14.2)

Performing a dimensional analysis for the power, P, shows

$$\frac{P}{\rho n^3 D^5} = f\left(\frac{V_0}{nD}, \frac{\rho D^2 n}{\mu}\right)$$


Power
Thrust
Blade Specifications
N = 1400 rpm
n = 23.3 rps
D = 2.90 m
Power, kW
Thrust, newtons
V0, m/s
0
10
20
30
40
500
1000
1500
2000
5
15
25

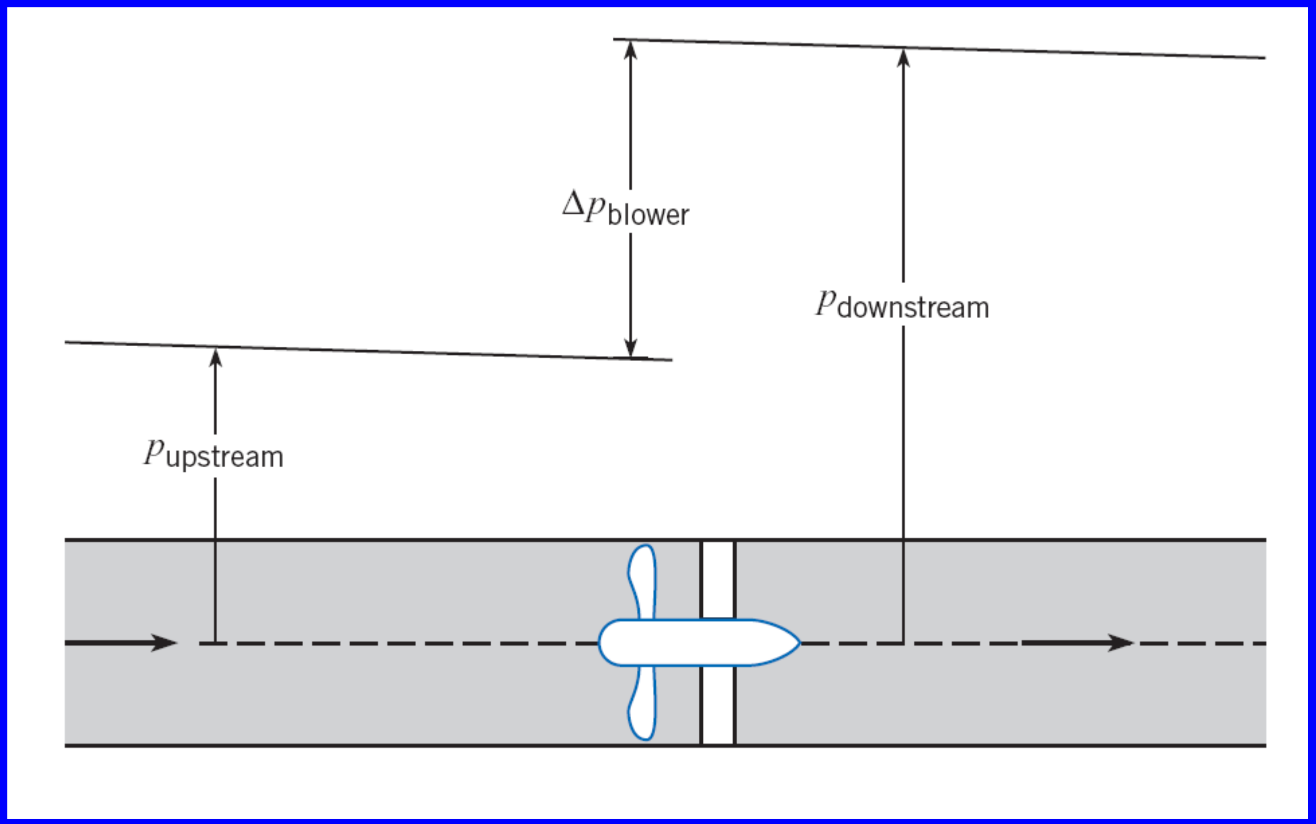
EFFICIENCY

The efficiency of a propeller is defined as the ratio of the power output— that is, thrust times velocity of advance—to the power input. Hence the efficiency η is given as

$$\eta = \frac{F_T V_0}{P} = \frac{C_T \rho D^4 n^2 V_0}{C_P \rho D^5 n^3}$$

$$\eta = \frac{C_T}{C_P}\left(\frac{V_0}{nD}\right) \qquad (14.11)$$

AXIAL FLOW PUMPS



Axial flow pumps are best suited for Low Heads and High Flow Rates

AXIAL FLOW PUMPS

Head and Discharge Coefficient for Pumps

Thrust Coefficient of a Pump = $C_T = \frac{F_T}{\rho D^4 n^2} = \frac{\Delta p\, A}{\rho D^4 n^2} = \frac{\gamma\, \Delta H A}{\rho D^4 n^2} = \frac{(\rho g)\Delta H}{\rho D^4 n^2}\left(\frac{\pi}{4} D^2\right) = \frac{\pi}{4}\frac{g\Delta H}{D^2 n^2}$

Head Coefficient of a Pump = $C_H = \frac{4}{\pi} C_T = \frac{\Delta H}{D^2 n^2 / g}$

Power Coefficient of a Pump = $C_P = \frac{P}{\rho D^5 n^3}$

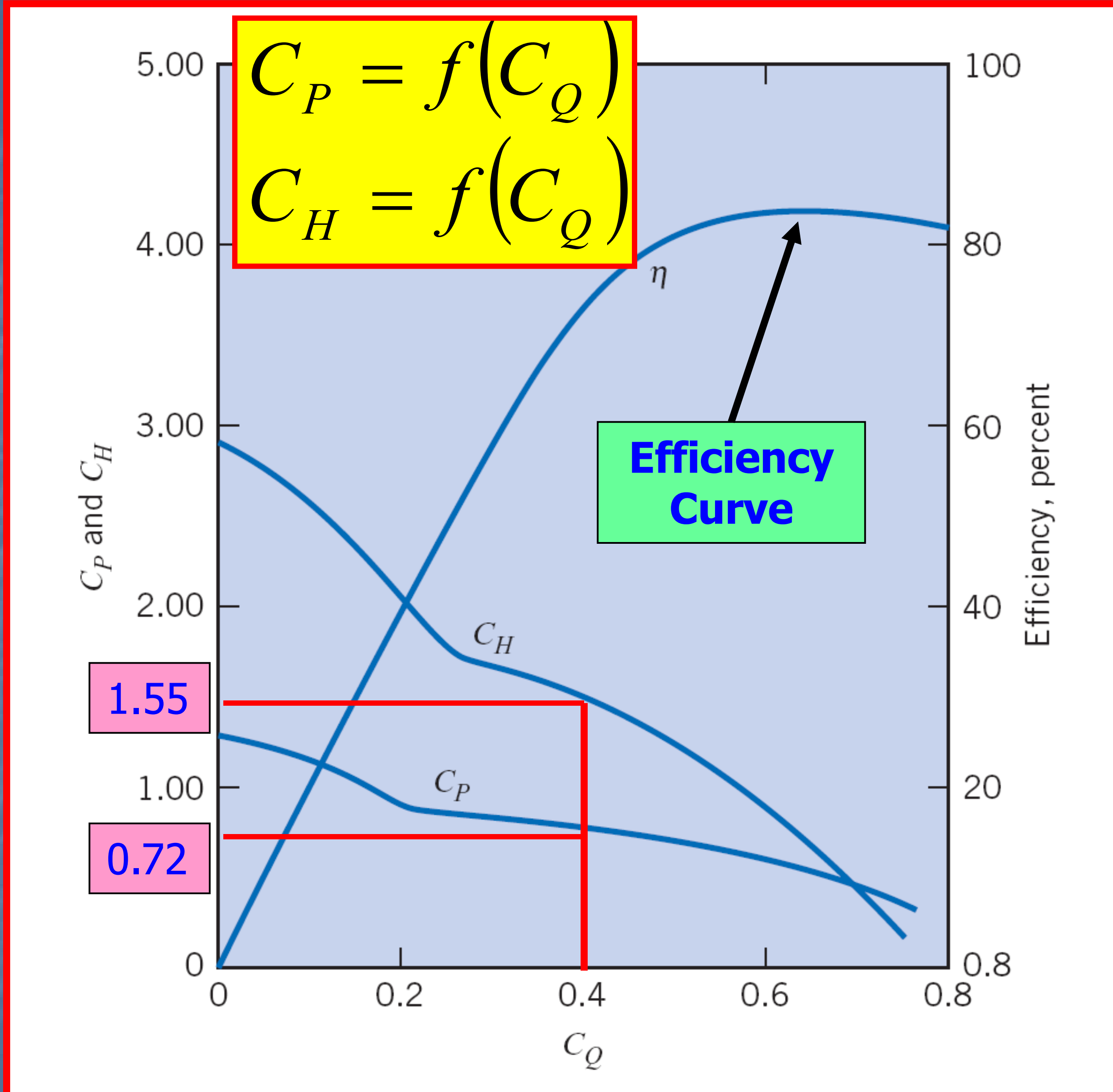
Discharge Coefficient of a Pump = $C_Q = \frac{Q}{n D^3}$

$$C_P = f(C_Q)$$
$$C_H = f(C_Q)$$

where C_H and C_P are functions of C_Q for a given type of pump.

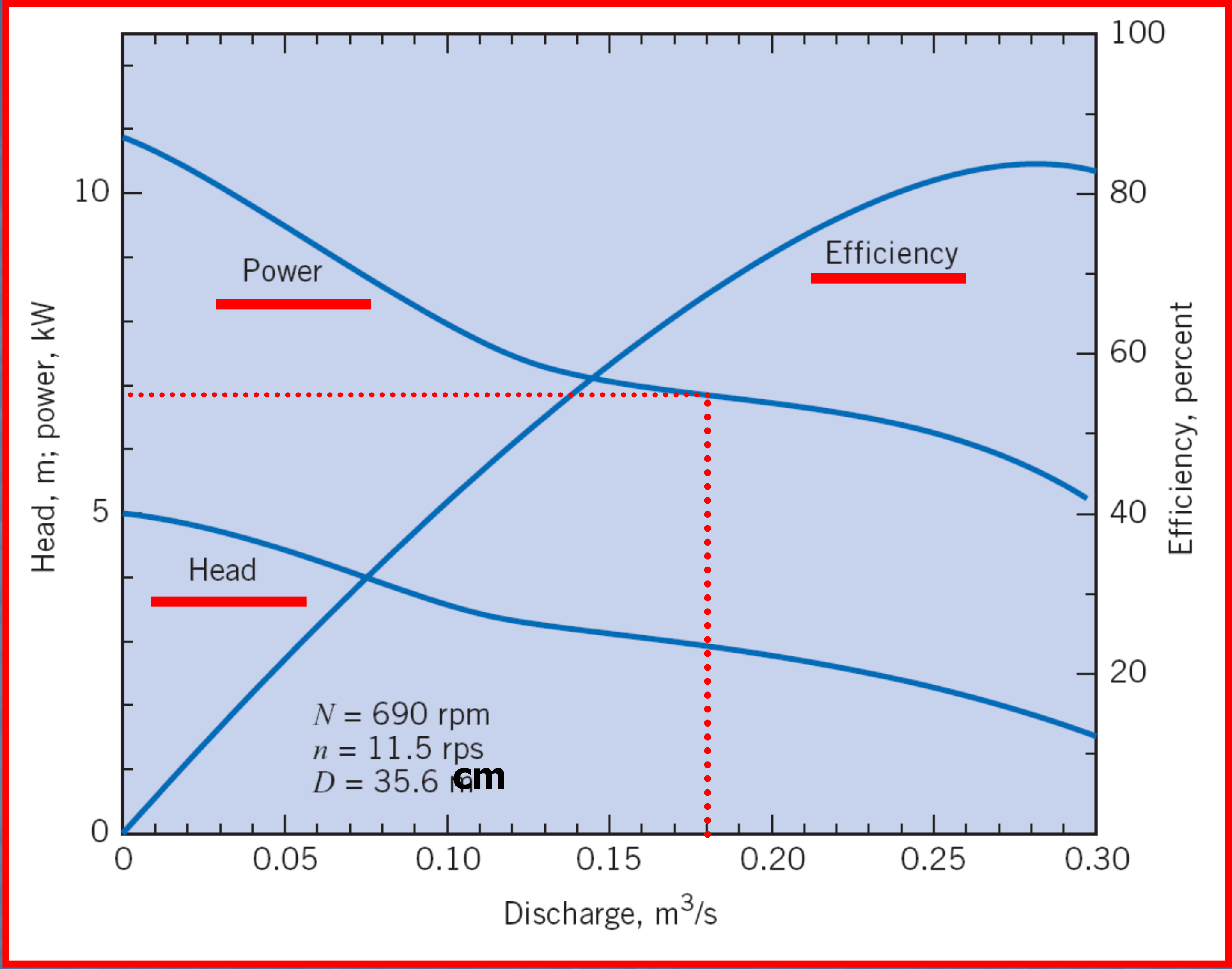
Fig. (14.6)

$$C_P = f(C_Q)$$
$$C_H = f(C_Q)$$



Dimensionless performance curves for a typical Axial-Flow Pump

Fig. (14.7)



Performance curves for a typical axial-flow pump

Radial - FLOW MACHINES

Centrifugal Pumps

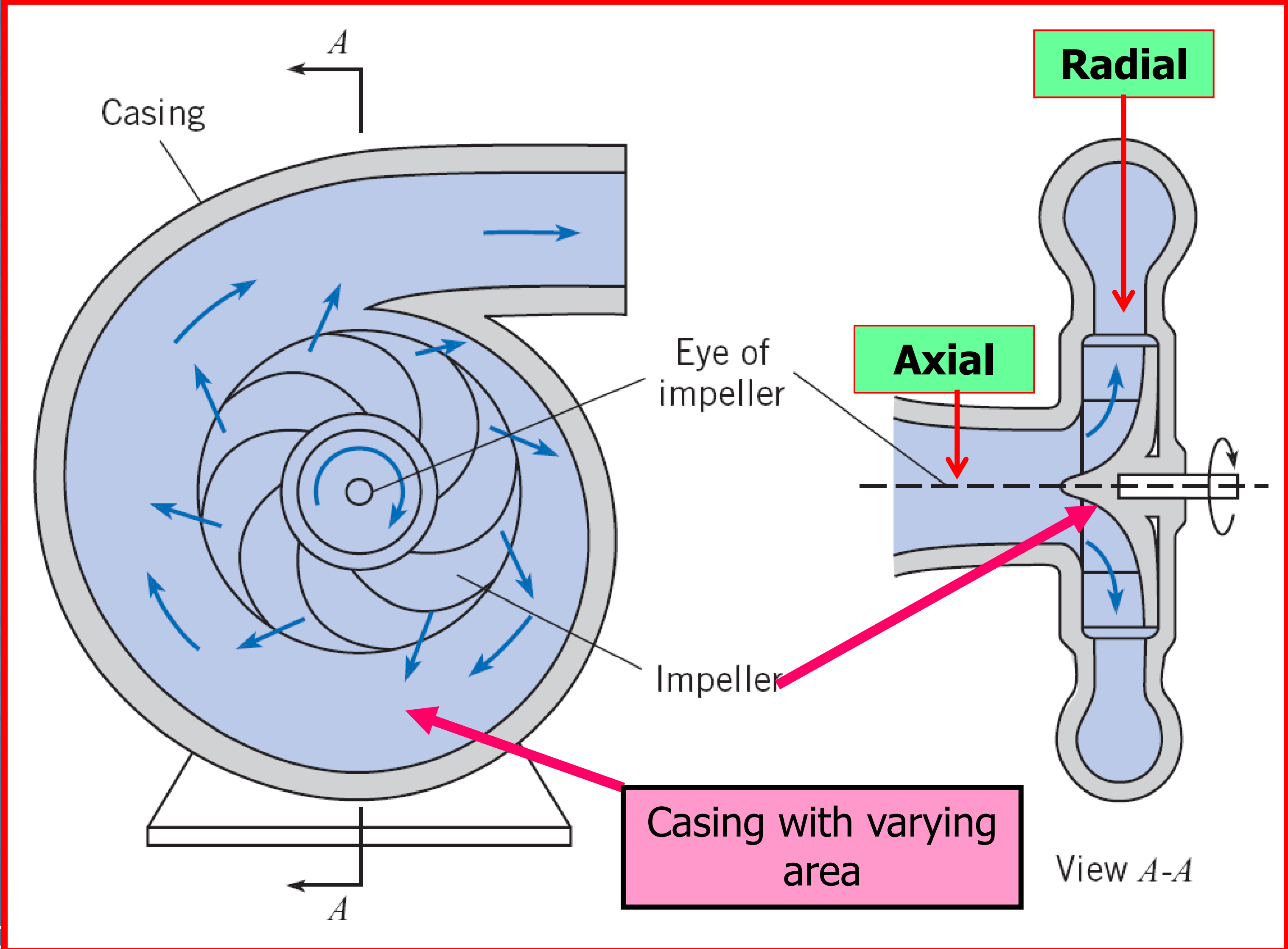
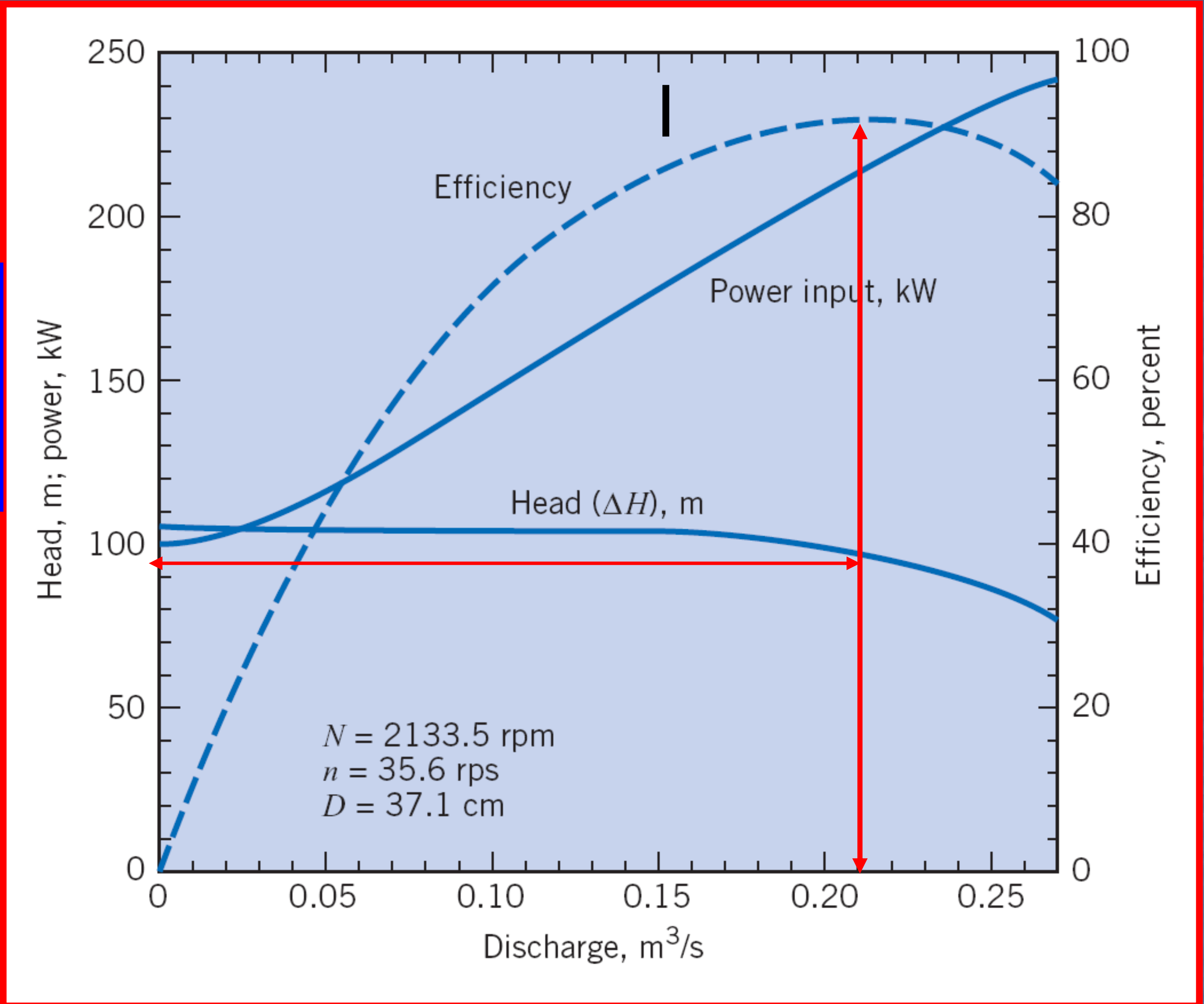
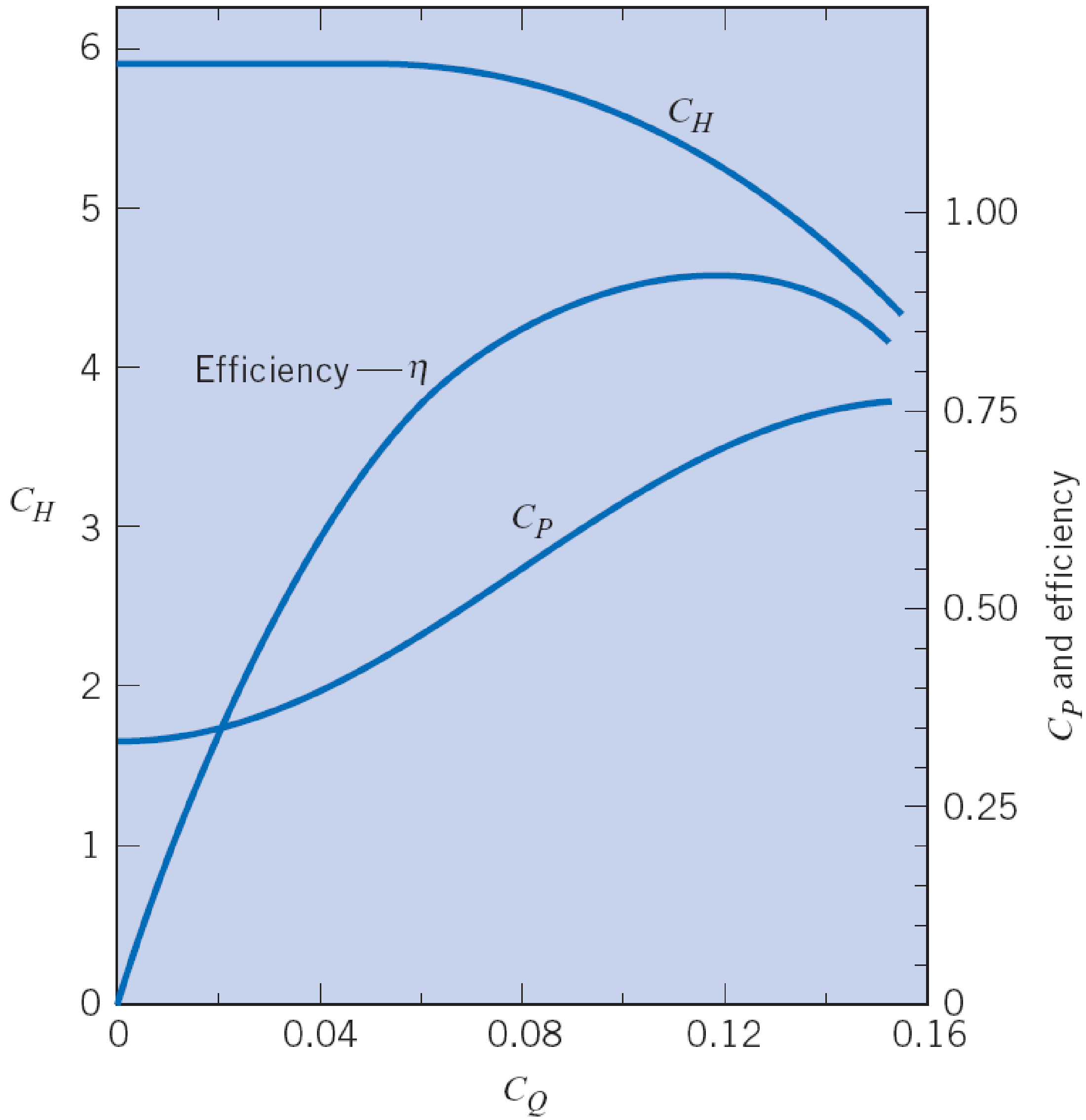


Fig. (14.9)



Performance curves for a typical centrifugal pump; *D* = 37.1 cm

Fig. (14.10)



Dimensionless performance curves for a typical centrifugal pump from data given in Fig. 14.9

SPECIFIC SPEED

The specific speed is a parameter used **to pick a type of a pump or a turbine** that is best used for a given application and is obtained as shown below

1. Axial Pump or Turbine used for Low Head, High Discharge

2. Radial Pump or Turbine used for High Head, Low Discharge

Specific speed is obtained by combining both both C_Q C_H

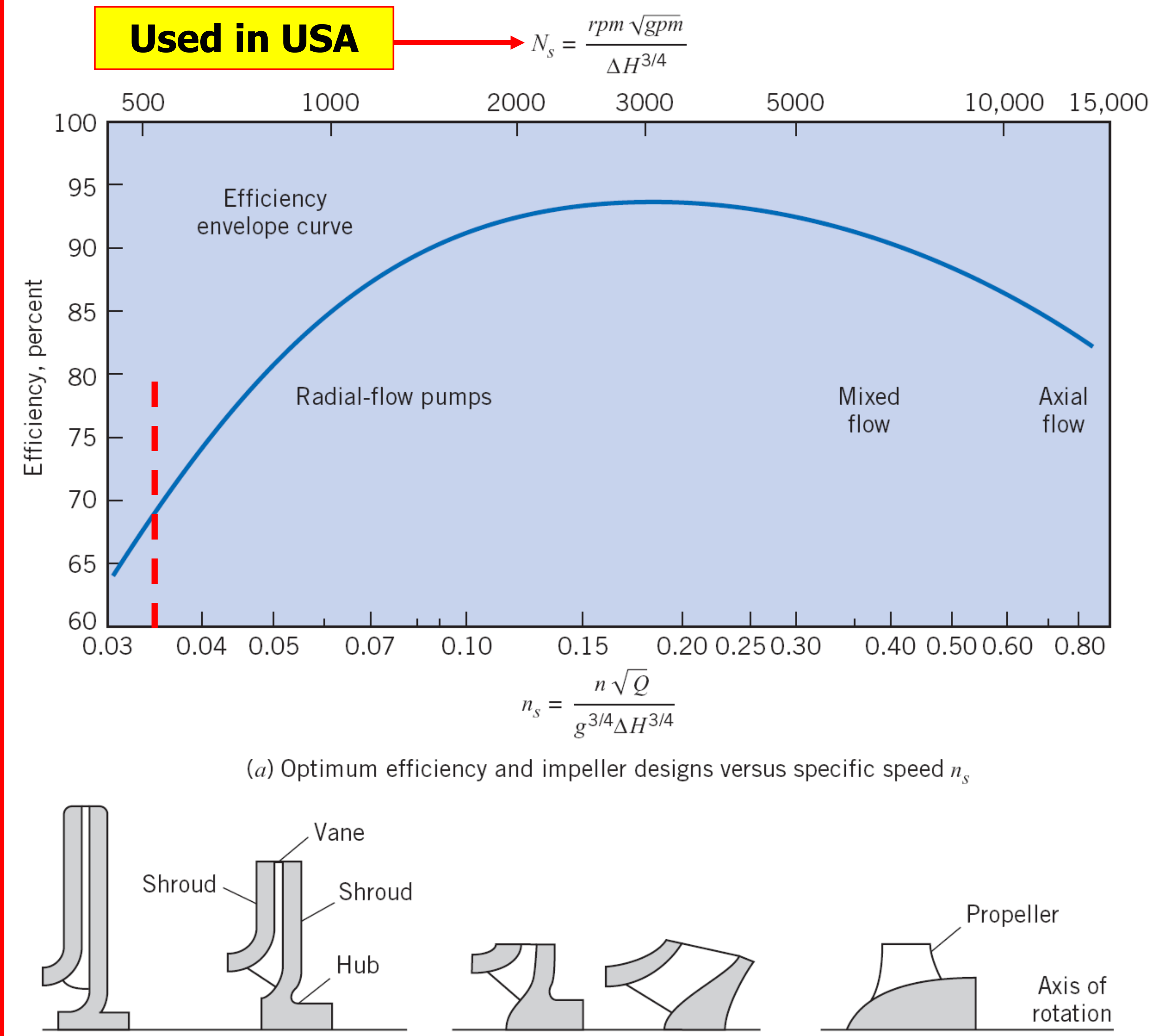
To eliminate the diameter (D)

$$C_H = \frac{\Delta H}{n^2 D^2 / g}$$

$$C_Q = \frac{Q}{nD^3}$$

$$n_s = \frac{C_Q^{1/2}}{C_H^{3/4}} = \frac{(Q/nD^3)^{1/2}}{[\Delta H/(D^2 n^2/g)]^{3/4}} = \frac{nQ^{1/2}}{g^{3/4}\Delta H^{3/4}}$$

Fig. (14.14)



(*a*) Optimum efficiency and impeller designs versus specific speed n_s

(*b*) Radial-flow impellers (*c*) Mixed-flow impellers (*d*) Axial flow

Suction Limitation of Pumps

The pressure at the suction side of the pump is most significant to avoid **Cavitation**

Cavitation usually occurs when the pressure of a flowing liquid equal the vapour pressure of the liquid at a given temperature.

More specifically, the pressure that is significant is the difference in pressure between the suction side of the pump and the vapor pressure of the liquid being pumped. Actually, in practice, engineers express this difference in terms of pressure head, called the *net positive suction head*, which is abbreviated *NPSH*. To calculate NPSH for a pump that is delivering a given discharge, one first applies the energy equation from the reservoir from which water is being pumped to the section of the intake pipe at the suction side of the pump. Then subtract the vapor pressure head of the water to determine NPSH.

In Fig. 14.15, points 1 and 2 are the points between which the energy equation would be written to evaluate NPSH.

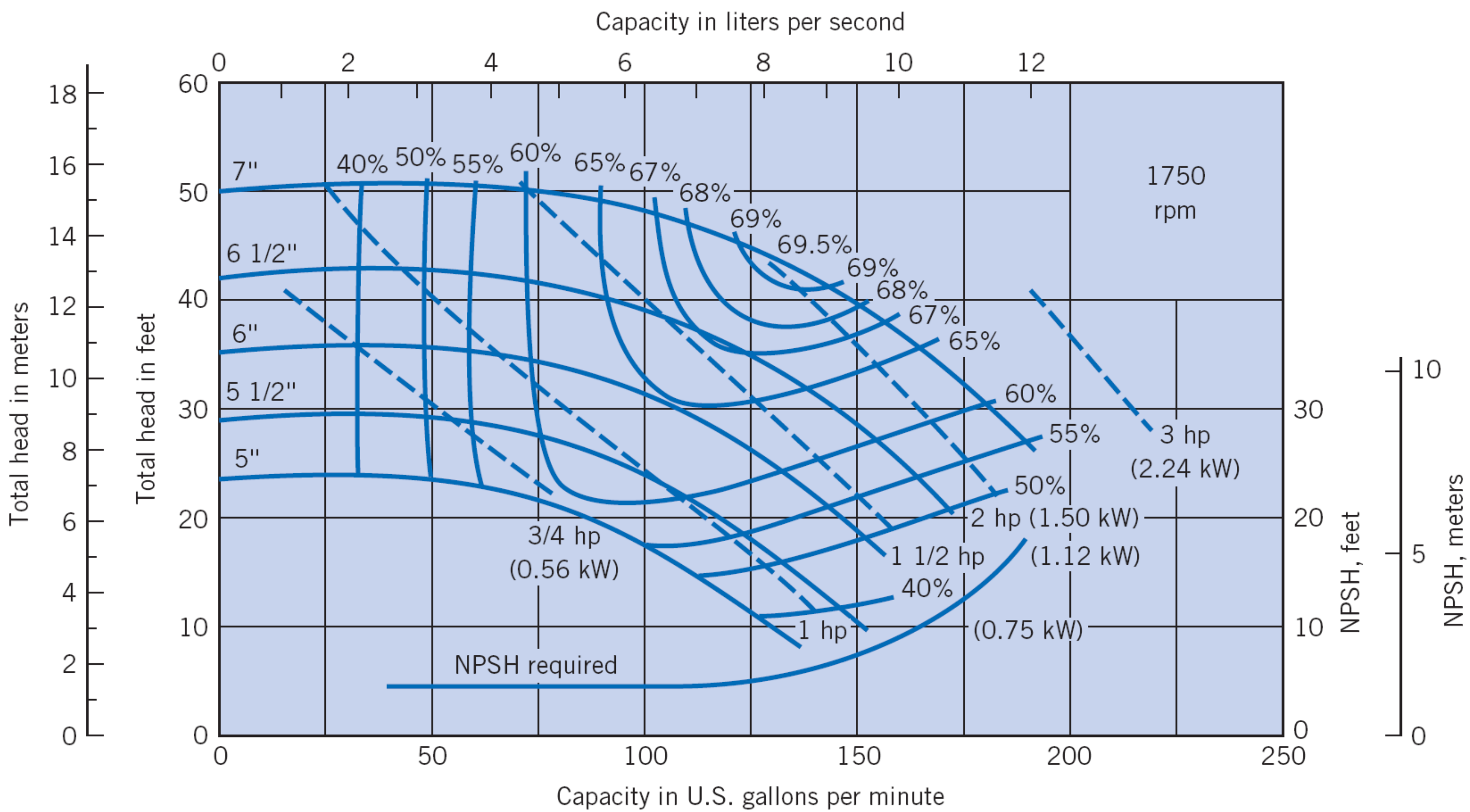
A more general parameter for indicating susceptibility to cavitation is specific speed. However, instead of using head produced (ΔH), one uses NPSH for the variable to the 3/4 power. This is

$$N_{SS} = \frac{NQ^{1/2}}{g^{3/4}(NPSH)^{3/4}}$$

$$Where\ N\,(rpm),\ Q\,(gpm),\ NPSH\,(feet)$$

Critical value for Cavitation to occur

$$(N_{SS} \leq 8500)$$



Centrifugal pump performance curve

Centrifugal Compressors

For an Ideal gas and Isentropic Compression process (Adiabatic and reversible)

The power required to compress the gas from (p_1) *to* (p_2)

$$P_{\text{theo}} = \frac{k}{k-1} Q_1 p_1 \left[\left(\frac{p_2}{p_1} \right)^{(k-1)/k} - 1 \right]$$

P_{theo} **is called the Theoretical Adiabatic Power with no cooling**

Efficiency of a compressor with no water cooling= $\eta_{Comp} = \dfrac{P_{theo}}{(P_{actual})_{SHAFT}}$

$$P_{\text{theo}} = p_1 Q_1 \ln \frac{p_2}{p_1}$$

P_{theo} **Is called the Theoretical Isothermal Power with cooling**

Turbines

A turbine is defined as a machine that extracts energy from a flowing fluid.

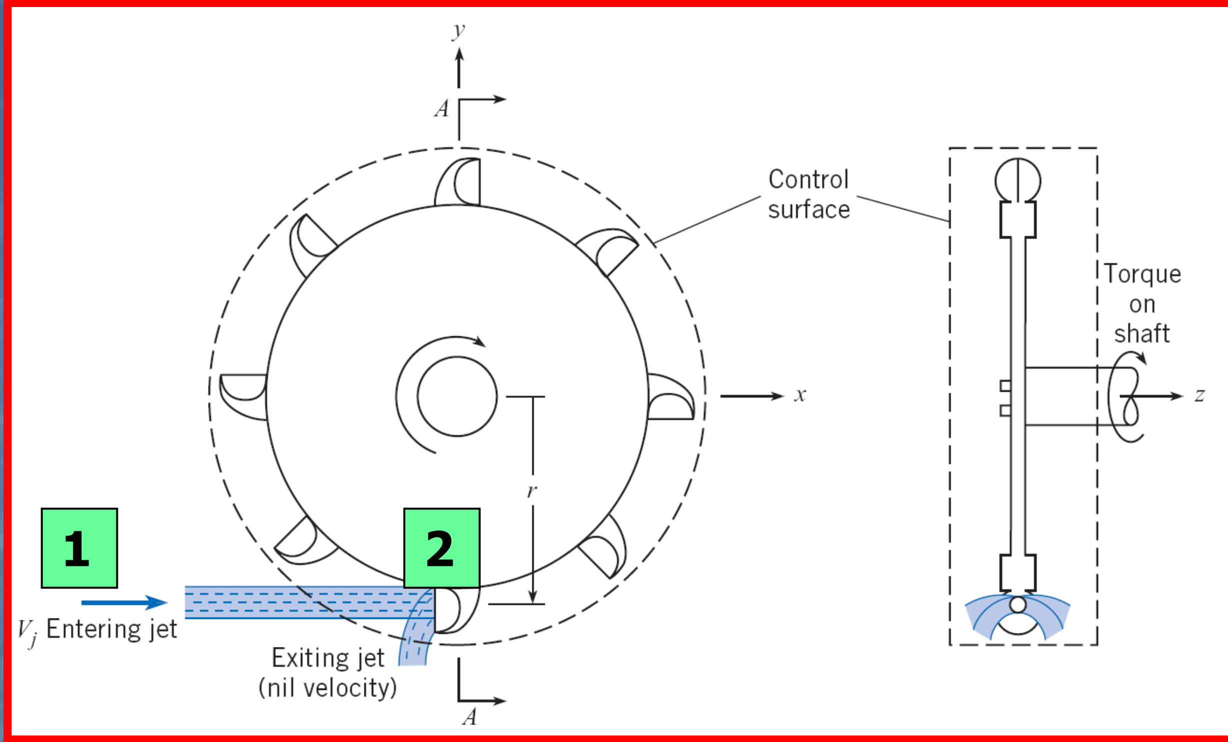
(a) Types of Turbines

1. Impulse Turbines.
2. Reaction Turbines.
3. Wind Turbines.

(b) Types of Turbines in relation to the direction of flow

1. Axial Kaplan Turbine. (Flow is axial).
2. Axial Pelton Turbine. (Flow is axial).
3. Radial Francis Turbine. (Flow is radial).

Pelton Wheel



Apply energy equation between (1) & (2), we have:

$$\left(h_1 + \frac{p_1}{\rho g} + z_1 + \alpha_1 \frac{\overline{V}_1^2}{2g}\right)_{Mech.part} = \left(h_T + \frac{p_2}{\rho g} + z_2 + \alpha_2 \frac{\overline{V}_2^2}{2g}\right)_{Mech.part} + h_{Loss}$$

If $h_{Loss} = 0$

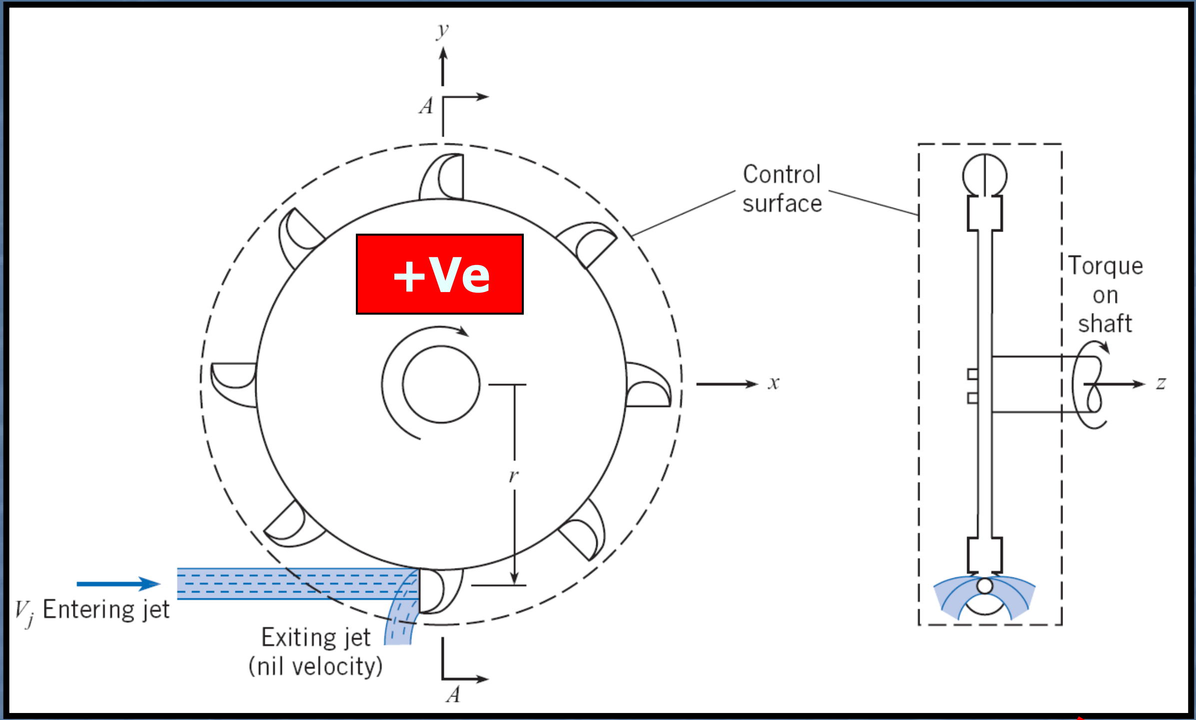
$$h_T = \frac{V_j^2}{2g}$$

$$V_1 = V_J$$

$$P_{Turbine} = \gamma Q h_T$$

$$P_{Turbine} = \gamma Q \frac{V_J^2}{2g}$$

Torque applied on the turbine shaft



Applying momentum Eqn. to a control volume

$$\sum M = \sum_{cs} \mathbf{r}_o \times (\dot{m}_o \mathbf{v}_o) - \sum_{cs} \mathbf{r}_i \times (\dot{m}_i \mathbf{v}_i)$$

It is assumed that the exiting velocity has a negligible momentum, then

$$T = -\dot{m} r V_j$$

The mass flow rate across the control volume is ρQ, so the torque is

$$T = -\rho Q V_j r$$

The minus sign indicates that the torque applied to the system (to keep it rotating at constant angular velocity) is in the clockwise direction. However, the torque applied by the system to the shaft is in the counterclockwise direction, which is the direction of wheel rotation, so

$$T = \rho Q V_j r$$

The power developed by the turbine is $T\omega$, or

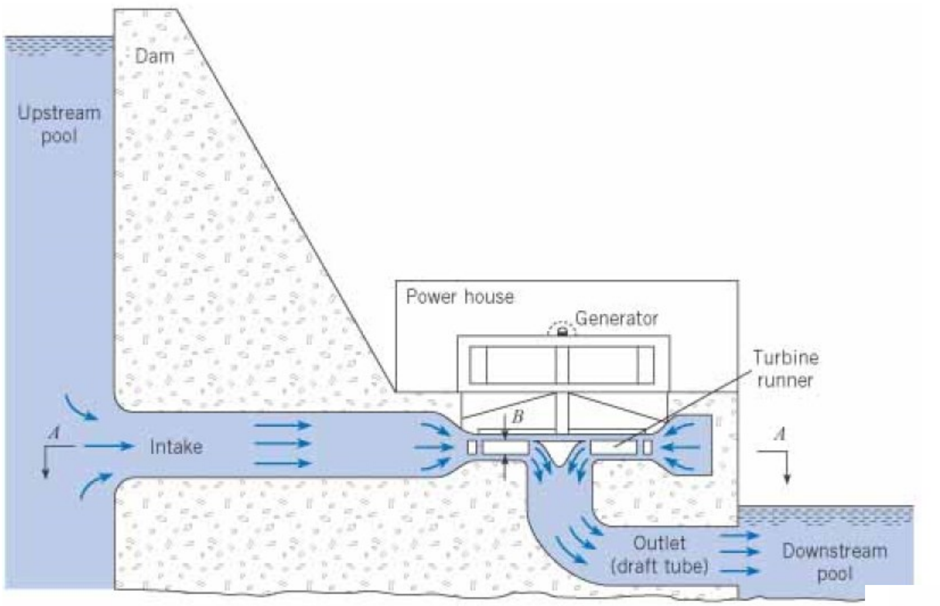
$$P = \rho Q V_j r \omega$$

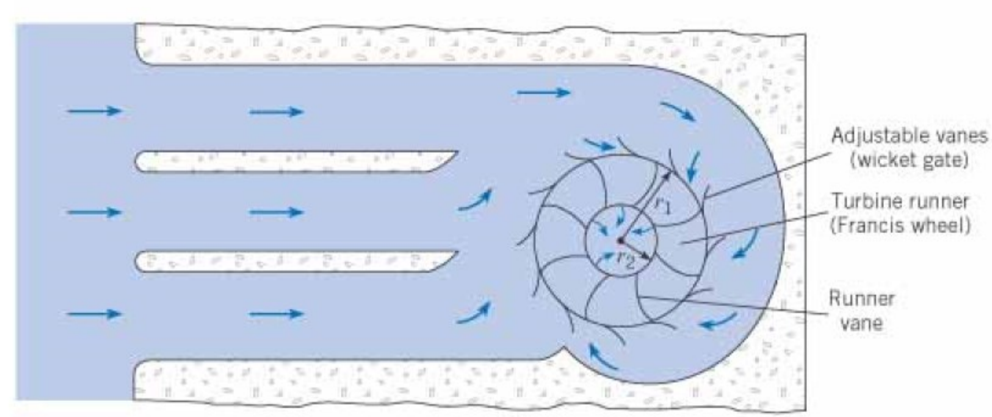
For Max. Power, $V_{Wheel} = (1/2) V_J$

Then: Max. Power of the Turbine $P = \rho Q \dfrac{V_J^{\,2}}{2}$

Reaction Turbine

1. The vanes of the reaction turbine are under pressure unlike the Impulse turbine where the pressure is atmospheric.
2. The flow fills the chamber in which the impeller is located.





(b)

The Torque and the power produced at the shaft is given below

$$T = \dot{m}(-r_2 V_2 \cos\alpha_2) - \dot{m}(-r_1 V_1 \cos\alpha_1)$$

$$= \dot{m}(r_1 V_1 \cos\alpha_1 - r_2 V_2 \cos\alpha_2)$$

The power from this turbine will be $T\omega$, or

$$P = \rho Q \omega (r_1 V_1 \cos\alpha_1 - r_2 V_2 \cos\alpha_2)$$

Eqn. (14.25)

Eqn. (14.25) is a function of the flow velocities directions α_1, α_2

Wind Turbines

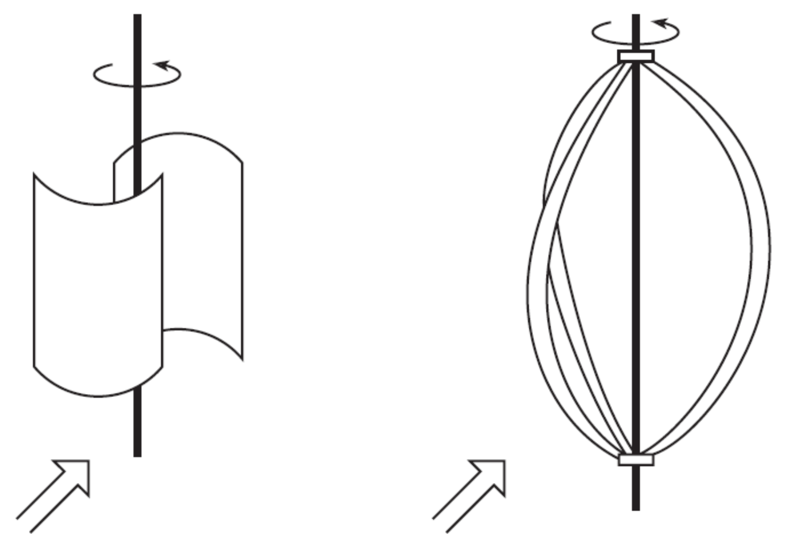
Wind Turbines: **Extracts energy from the wind to produce Power**

The max. theoretical power produced by a wind turbine

$$P_{max} = \frac{16}{27}\left(\frac{1}{2}\rho U^3 A\right)$$

U: Wind speed

A: Area captured by the wind turbine



(a) Savonius rotor (b) Darrieus turbine

END OF CHAPTER (14)