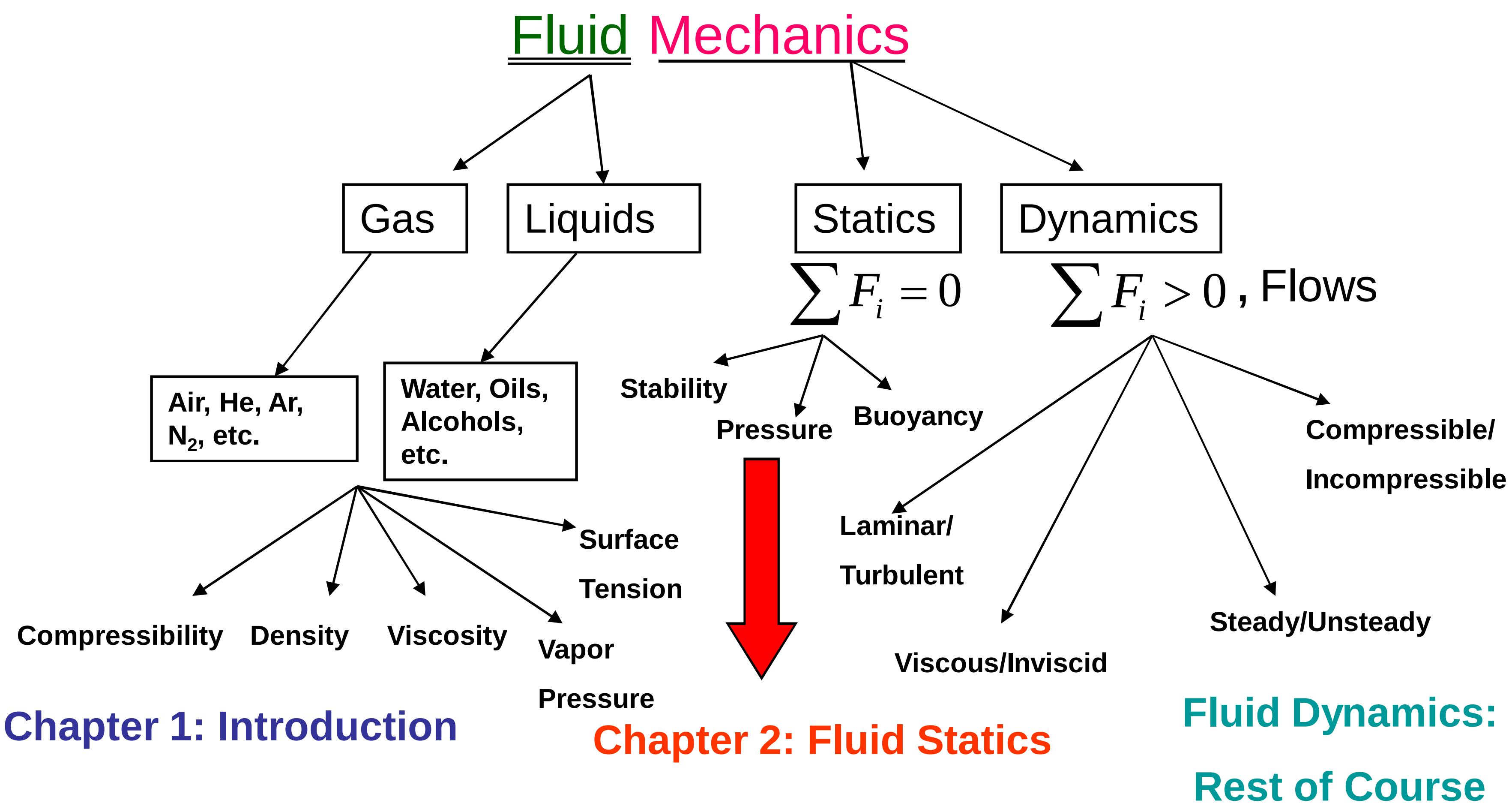
FLUID MECHANICS

- Syllabus (Hand-Out)
- Fluid Mechanics Overview
- Characteristics of Fluids
- Measures of Fluid Mass and Weight
- Viscosity
- Compressibility
- Vapor Pressure
- Surface Tension

Fluid Mechanics Overview



Characteristics of Fluids

- Gas or liquid state
- “Large” molecular spacing relative to a solid 
- “Weak” intermolecular cohesive forces
- Can not resist a shear stress in a stationary state
- Will take the shape of its container
- Generally considered a continuum
- Viscosity distinguishes different types of fluids

Measures of Fluid Mass and Weight: Density

The density of a fluid is defined as mass per unit volume.

$$\rho = \frac{m}{v}$$

m = mass, and v = volume.

- Different fluids can vary greatly in density
- Liquids densities do not vary much with pressure and temperature
- Gas densities can vary quite a bit with pressure and temperature
- Density of water at 4° C : 1000 kg/m^3
- Density of Air at 4° C : 1.20 kg/m^3

Alternatively, **Specific Volume**: $$\upsilon = \frac{1}{\rho}$$

Measures of Fluid Mass and Weight: Specific Weight

The specific weight of fluid is its weight per unit volume.

$$\gamma = \rho g$$

g = local acceleration of gravity, 9.807 m/s^2

- Specific weight characterizes the weight of the fluid system
- Specific weight of water at 4° C : 9.80 kN/m^3
- Specific weight of air at 4° C : 11.9 N/m^3

Measures of Fluid Mass and Weight: Specific Gravity

The specific gravity of fluid is the ratio of the density of the fluid to the density of water @ 4° C.

$$SG = \frac{\rho}{\rho_{H_2O}}$$

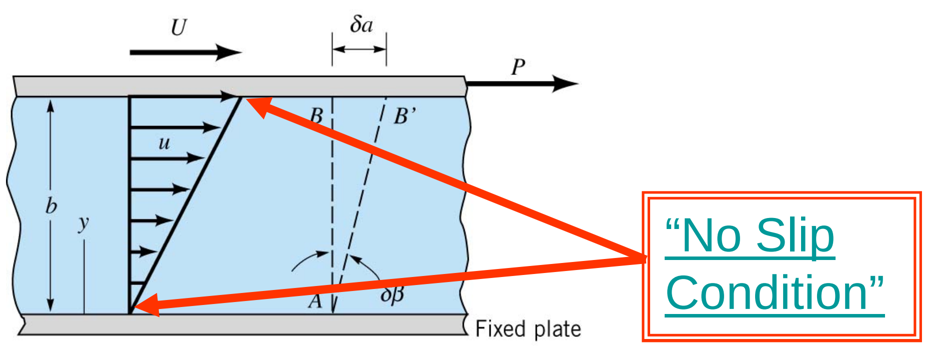
- Gases have low specific gravities
- A liquid such as Mercury has a high specific gravity, 13.2
- The ratio is unitless.
- Density of water at 4° C : 1000 kg/m^3

Viscosity: Introduction

The viscosity is measure of the "fluidity" of the fluid which is not captured simply by density or specific weight. A fluid can not resist a shear and under shear begins to flow. The shearing stress and shearing strain can be related with a relationship of the following form for common fluids such as water, air, oil, and gasoline:

$$\tau = \mu \frac{du}{dy}$$

μ is the absolute viscosity or dynamics viscosity of the fluid, u is the velocity of the fluid and y is the vertical coordinate as shown in the schematic below:



Viscosity: Measurements

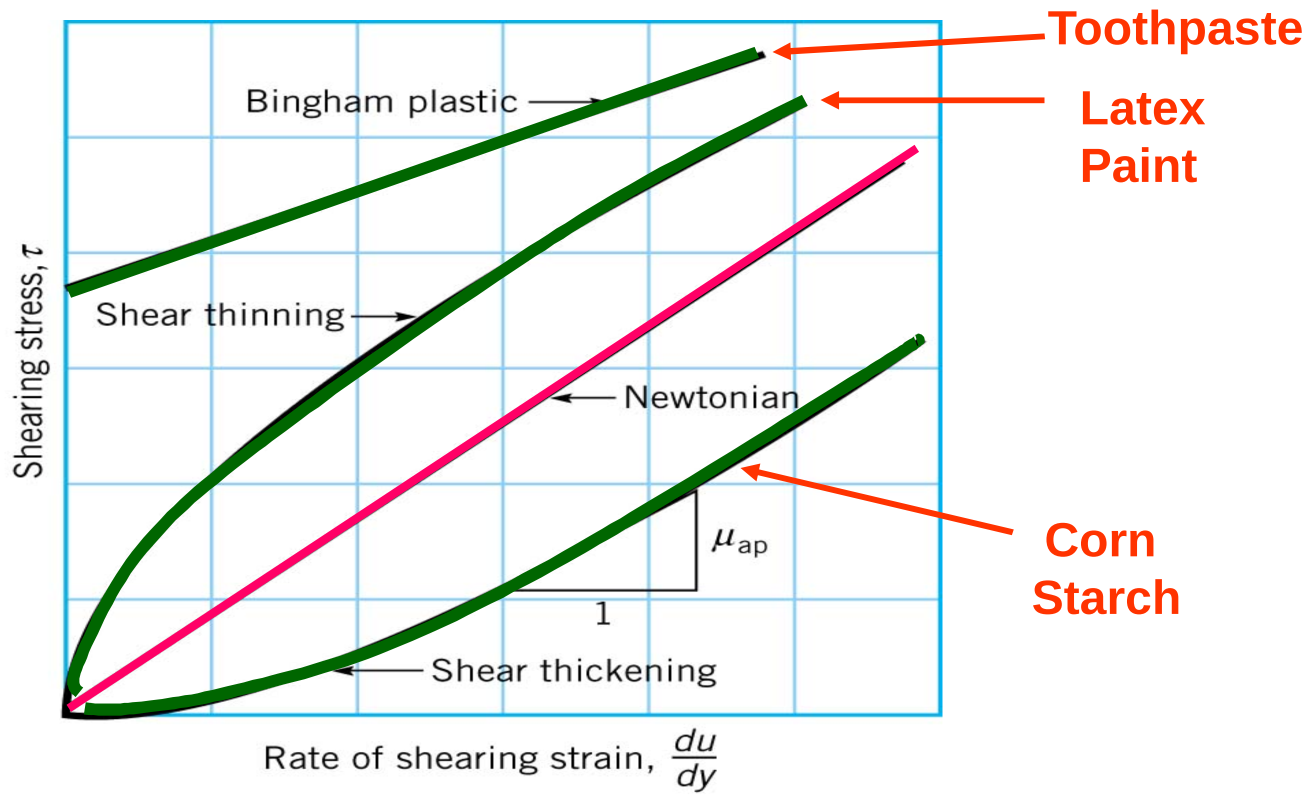
A Capillary Tube Viscosimeter is one method of measuring the viscosity of the fluid.

Viscosity Varies from Fluid to Fluid and is dependent on temperature, thus temperature is measured as well.

Units of Viscosity are $N \cdot s/m^2$ or $lb \cdot s/ft^2$

Movie Example using a Viscosimeter:

Viscosity: Newtonian vs. Non-Newtonian



Newtonian Fluids are Linear Relationships between stress and strain: Most common fluids are Newtonian.

Non-Newtonian Fluids are Non-Linear between stress and strain

Viscosity: Kinematic Viscosity

$$\nu = \frac{\mu}{\rho}$$

- Kinematic viscosity is another way of representing viscosity
- Used in the flow equations
- The units are of L^2/T or m^2/s and ft^2/s

Compressibility of Fluids: Bulk Modulus

$$E_{\upsilon} = \frac{dp}{d\rho / \rho}$$

P is pressure, and ρ is the density.

- Measure of how pressure compresses the volume/density
- Units of the bulk modulus are N/m^2 (Pa) and lb/in.^{2} (psi).
- Large values of the bulk modulus indicate incompressibility
- Incompressibility indicates large pressures are needed to compress the volume slightly
- It takes 3120 psi to compress water 1% at atmospheric pressure and 60° F.
- Most liquids are incompressible for most practical engineering problems.

Compressibility of Fluids: Compression of Gases

Ideal Gas Law: $p = \rho R T$

P is pressure, ρ is the density, R is the gas constant, and T is Temperature

Isothermal Process (constant temperature):

$$\frac{p}{\rho} = constant \quad \xrightarrow{\text{Math}} \quad E_{\upsilon} = p$$

Isentropic Process (frictionless, no heat exchange):

$$\frac{p}{\rho^{k}} = constant \quad \xrightarrow{\text{Math}} \quad E_{\upsilon} = kp$$

k is the ratio of specific heats, c_p (constant pressure) to c_v (constant volume), and $R = c_p - c_v$.

If we consider air under at the same conditions as water, we can show that air is 15,000 times more compressible than water. However, many engineering applications allow air to be considered incompressible.

Compressibility of Fluids: Speed of Sound

A consequence of the compressibility of fluids is that small disturbances introduced at a point propagate at a finite velocity. Pressure disturbances in the fluid propagate as sound, and their velocity is known as the speed of sound or the acoustic velocity, c.

$$c = \sqrt{\frac{dp}{d\rho}} \quad or \quad c = \sqrt{\frac{E_v}{\rho}}$$

Isentropic Process (frictionless, no heat exchange because):

$$c = \sqrt{\frac{kp}{\rho}}$$

Ideal Gas and Isentropic Process:

$$c = \sqrt{kRT}$$

Compressibility of Fluids: Speed of Sound

- Speed of Sound in Air at 60 °F ≈ 1117 ft/s or 300 m/s
- Speed of Sound in Water at 60 °F ≈ 4860 ft/s or 1450 m/s
- If a fluid is truly incompressible, the speed of sound is infinite, however, all fluids compress slightly.

Example: A jet aircraft flies at a speed of 250 m/s at an altitude of 10,700 m, where the temperature is -54 °C. Determine the ratio of the speed of the aircraft, V, to the speed of sound, c at the specified altitude. Assume k = 1.40

Ideal Gas and Isentropic Process:

$$c = \sqrt{kRT}$$

$$c = \sqrt{1.40 * (286.9 \ \ J/kgK) * 219 \ \ K}$$

$$c = 296.6 \ \ m/s$$

Compressibility of Fluids: Speed of Sound

Example (Continued):

$$Ratio = \frac{V}{c}$$

$$Ratio = \frac{250 \ \ m/s}{296.6 \ \ m/s}$$

$$Ratio = 0.84$$

- The above ratio is known as the Mach Number, Ma
- For Ma < 1 ***Subsonic Flow***
- For Ma > 1 ***Supersonic Flow***

For Ma > 1 we see shock waves and “sonic booms”:

1) Wind Tunnel Visualization known as Schlieren method
2) Condensation instigated from jet speed allowing us to see a shock wave 

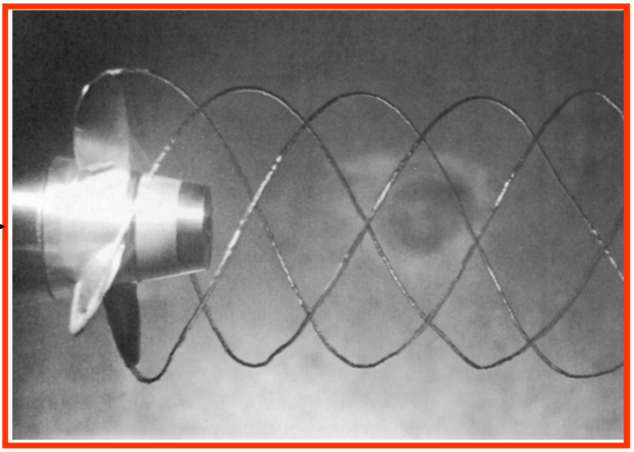
Vapor Pressure: Evaporation and Boiling

Evaporation occurs in a fluid when liquid molecules at the surface have sufficient momentum to overcome the intermolecular cohesive forces and escape to the atmosphere.

Vapor Pressure is that pressure exerted on the fluid by the vapor in a closed saturated system where the number of molecules entering the liquid are the same as those escaping. Vapor pressure depends on temperature and type of fluid.

Boiling occurs when the absolute pressure in the fluid reaches the vapor pressure. Boiling occurs at approximately 100 °C, but it is not only a function of temperature, but also of pressure. For example, in Colorado Spring, water boils at temperatures less than 100 °C.

Cavitation is a form of Boiling due to low pressure locally in a flow.



Surface Tension

At the interface between a liquid and a gas or two immiscible liquids, forces develop forming an analogous "skin" or "membrane" stretched over the fluid mass which can support weight.

This "skin" is due to an imbalance of cohesive forces. The interior of the fluid is in balance as molecules of the like fluid are attracting each other while on the interface there is a net inward pulling force.

Surface tension is the intensity of the molecular attraction per unit length along any line in the surface.

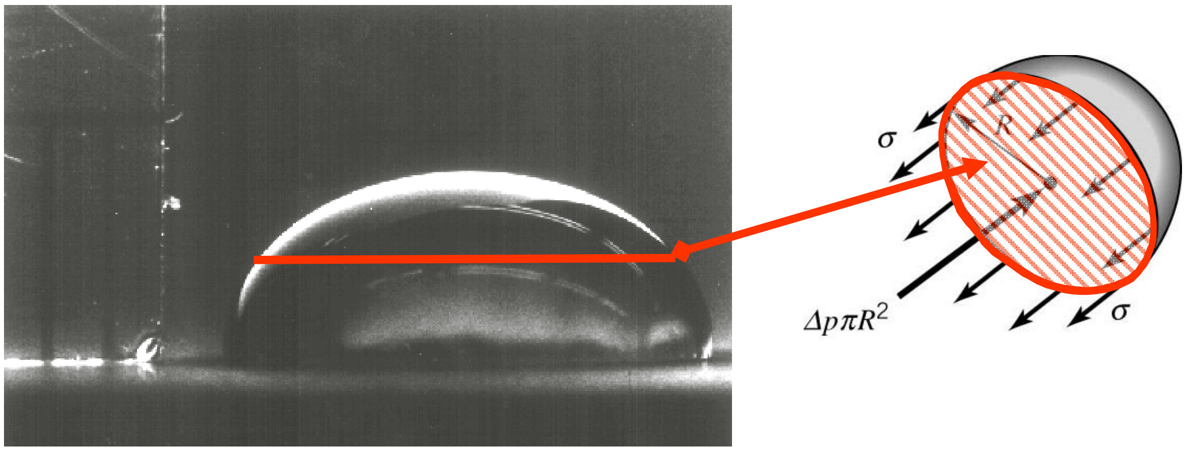
Surface tension is a property of the liquid type, the temperature, and the other fluid at the interface.

This membrane can be "broken" with a surfactant which reduces the surface tension.

Surface Tension: Liquid Drop

The pressure inside a drop of fluid can be calculated using a free-body diagram:

Real Fluid Drops | Mathematical Model



R is the radius of the droplet, σ is the surface tension, Δp is the pressure difference between the inside and outside pressure.

The force developed around the edge due to surface tension along the line:

$$F_{surface} = 2\pi R\sigma$$

Applied to Circumference

This force is balanced by the pressure difference Δp:

$$F_{pressure} = \Delta p \pi R^2$$

Applied to Area

Surface Tension: Liquid Drop

Now, equating the Surface Tension Force to the Pressure Force, we can estimate $\Delta p = p_i - p_e$:

$$\Delta p = \frac{2\sigma}{R}$$

This indicates that the internal pressure in the droplet is greater that the external pressure since the right hand side is entirely positive.

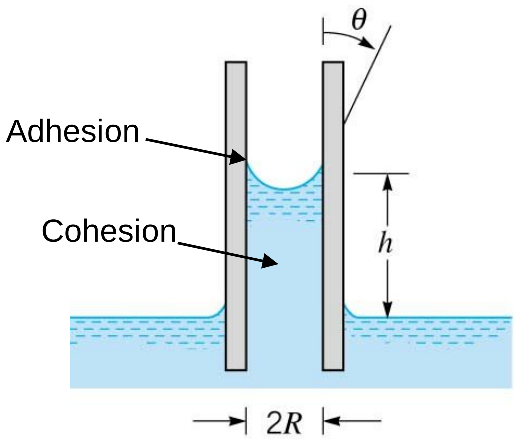
Is the pressure inside a bubble of water greater or less than that of a droplet of water?

Prove to yourself the following result: $\Delta p = \frac{4\sigma}{R}$

Surface Tension: Capillary Action

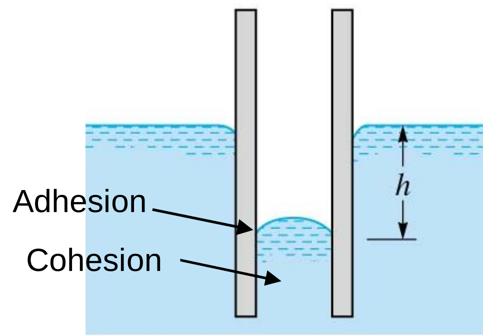
Capillary action in small tubes which involve a liquid-gas-solid interface is caused by surface tension. The fluid is either drawn up the tube or pushed down.

“Wetted”



Adhesion > Cohesion

“Non-Wetted”



Cohesion > Adhesion

h is the height, R is the radius of the tube, θ is the angle of contact.

The weight of the fluid is balanced with the vertical force caused by surface tension.

Flow In Circular Pipes

Objective

- To measure the pressure drop in the straight section of smooth, rough, and packed pipes as a function of flow rate.
- To correlate this in terms of the friction factor and Reynolds number.
- To compare results with available theories and correlations.
- To determine the influence of pipe fittings on pressure drop
- To show the relation between flow area, pressure drop and loss as a function of flow rate for Venturi meter and Orifice meter.

APPARATUS

Pipe Network
Rotameters
Manometers

Theoretical Discussion

Fluid flow in pipes is of considerable importance in process.

- •Animals and Plants circulation systems.
- •In our homes.
- •City water.
- •Irrigation system.
- •Sewer water system

➢ Fluid could be a single phase: liquid or gases

Mixtures of gases, liquids and solids

➢ **NonNewtonian** fluids such as polymer melts, mayonnaise

➢ **Newtonian** fluids like in your experiment (water)

Theoretical Discussion
Laminar flow

To describe any of these flows, conservation of mass and conservation of momentum equations are the most general forms could be used to describe the dynamic system. Where the key issue is the **relation between flow rate and pressure drop.**

If the flow fluid is:

a. Newtonian
b. Isothermal
c. Incompressible (dose not depend on the pressure)
d. Steady flow (independent on time).
e. Laminar flow (the velocity has only one single component)

Laminar flow

Navier-Stokes equations is govern the flow field (a set of equations containing only velocity components and pressure) and can be solved exactly to obtain the **Hagen-Poiseuille relation**

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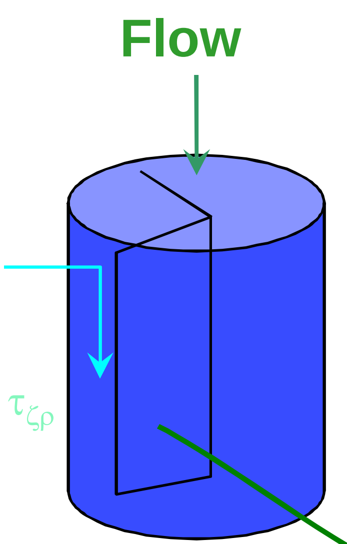
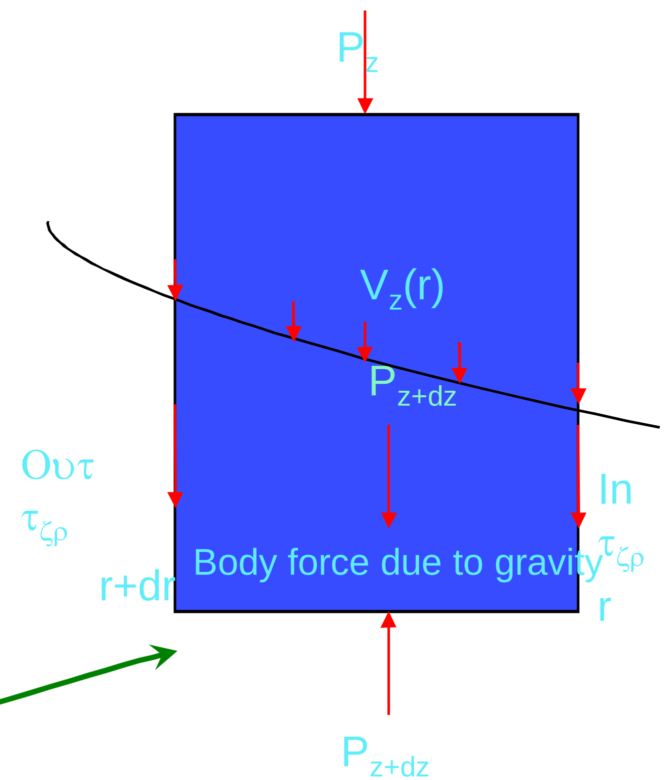


If the principle of conservation of momentum is applied to a fixed volume element through which fluid is flowing and on which forces are acting, then the forces must be balanced (Newton second law)



Laminar flow
Continue

Forces balance

[redacted]

[redacted]

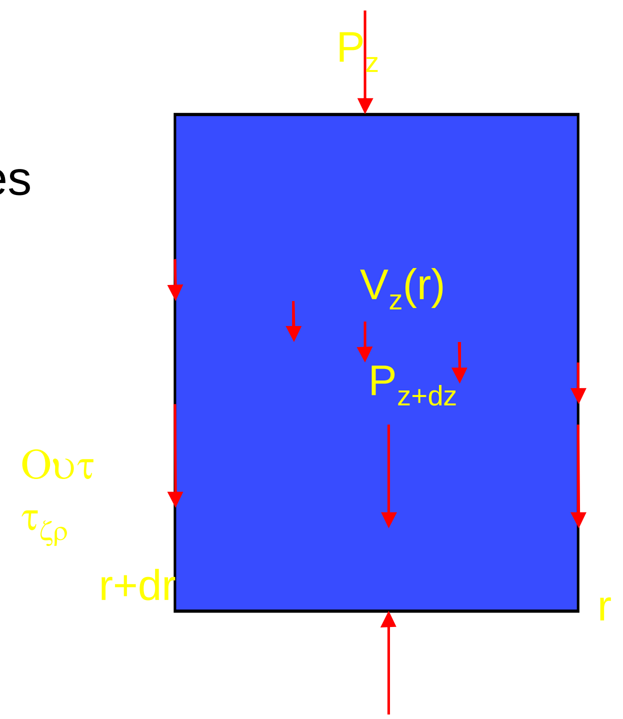
1…Shear forces

[redacted]

2….Pressure

[redacted]

3…..Body force



Laminar flow Continue

Momentum is
Mass*velocity ***(m*v)***
Momentum per unit volume is

$$\rho * v_z$$

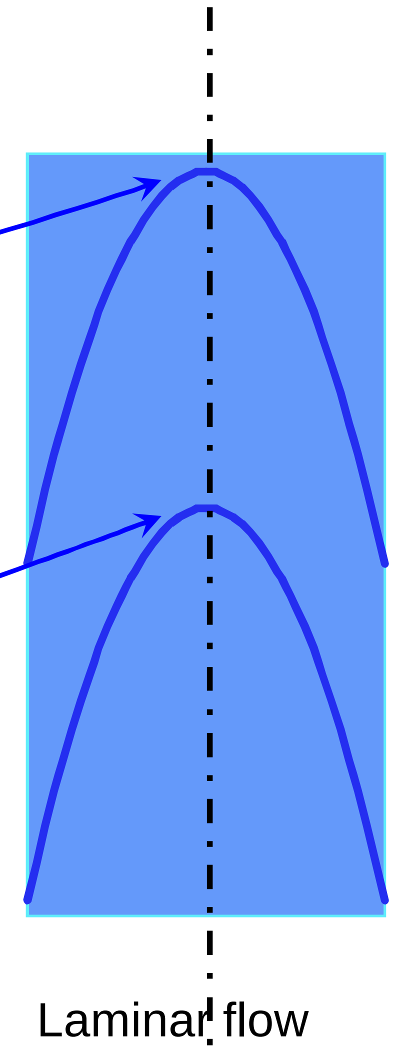
Rate of flow of momentum is

$$\rho * v_z * dQ$$

$$dQ = v_z 2\pi r dr$$

but

v_z = constant at a fixed value of r



Laminar flow
Continue

[redacted]

[redacted]

[redacted]

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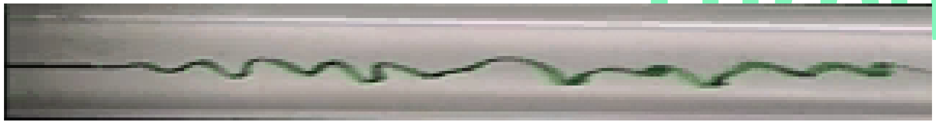
Hagen-Poiseuille

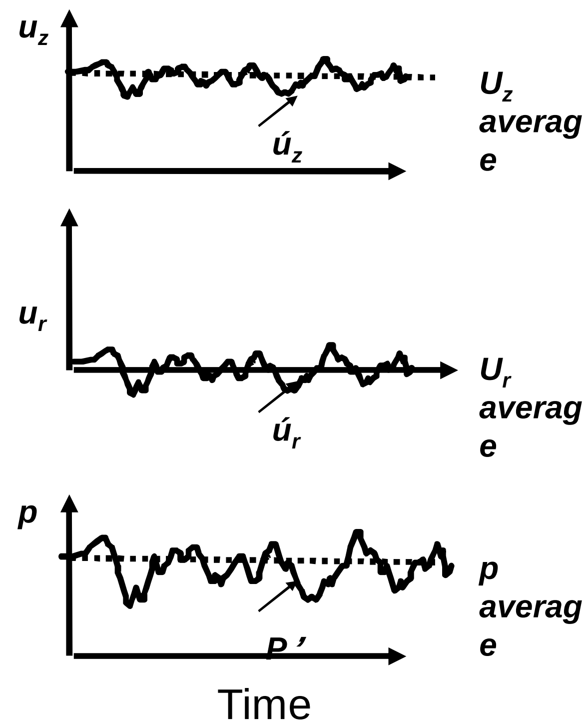
Turbulent flow



➢When fluid flow at higher flowrates, the streamlines are not steady and straight and the flow is not laminar. Generally, the flow field will vary in both space and time with fluctuations that comprise "turbulence

➢For this case almost all terms in the Navier-Stokes equations are important and there is no simple solution

$$\Delta P = \Delta P\ (D, \mu, \rho, L, U,)$$



Turbulent flow

All previous parameters involved three fundamental dimensions,

Mass, length, and time

From these parameters, three dimensionless groups can be build

[redacted]

$$\mathrm{Re} = \frac{\rho U D}{\mu} = \frac{\text{inertia}}{\text{Viscous forces}}$$

Friction Factor for Laminar Turbulent flows

From forces balance and the definition of Friction Factor

$$\Delta P \times A_c = \bar{\tau} \times S \times L$$

$$\frac{A_c}{S} = r_h = \frac{1}{4} D$$

$$\bar{\tau} = \frac{\Delta P}{2L} R$$

A_c: cross section area of the pip

S: Perimeter on which *T acts (wetted perimeter)*

R_h *hydraulic radius*

$$f = \frac{\bar{\tau}}{1/2 \rho U^2}$$

$$f = \frac{\Delta \bar{P} R}{\rho U^2 L}$$

For Laminar flow (Hagen - Poiseuill eq)

$$Q = \frac{\pi r^4}{8\mu} \frac{\Delta P}{L}$$

$$\frac{\Delta P}{L} = \frac{8 \mu U}{R^2}$$

[redacted]

For Turbulent Flow

$$f = \frac{\Delta P}{L} \frac{D}{2 \rho U^2} = 0.079 \mathrm{Re}^{-0.25}$$

Turbulence: Flow Instability

- In turbulent flow (high Reynolds number) the force leading to stability (viscosity) is small relative to the force leading to instability (inertia).
- Any disturbance in the flow results in large scale motions superimposed on the mean flow.
- Some of the kinetic energy of the flow is transferred to these large scale motions (eddies).
- Large scale instabilities gradually lose kinetic energy to smaller scale motions.
- The kinetic energy of the smallest eddies is dissipated by viscous resistance and turned into heat. (=head loss)

Velocity Distributions

- Turbulence causes transfer of momentum from center of pipe to fluid closer to the pipe wall.
- Mixing of fluid (transfer of momentum) causes the central region of the pipe to have relatively constant velocity (compared to laminar flow)
- Close to the pipe wall eddies are smaller (size proportional to distance to the boundary)

Surface Roughness

Additional dimensionless group **ε/D** need to be characterize

Thus more than one curve on friction factor-Reynolds number plot

↓

Fanning diagram or Moody diagram

Depending on the laminar region.

If, at the lowest Reynolds numbers, the laminar portion corresponds to $f = 16/Re$ Fanning Chart

or $f = 64/Re$ Moody chart

Friction Factor for Smooth, Transition, and Rough Turbulent flow

[redacted]

Smooth pipe, Re>3000

[redacted]

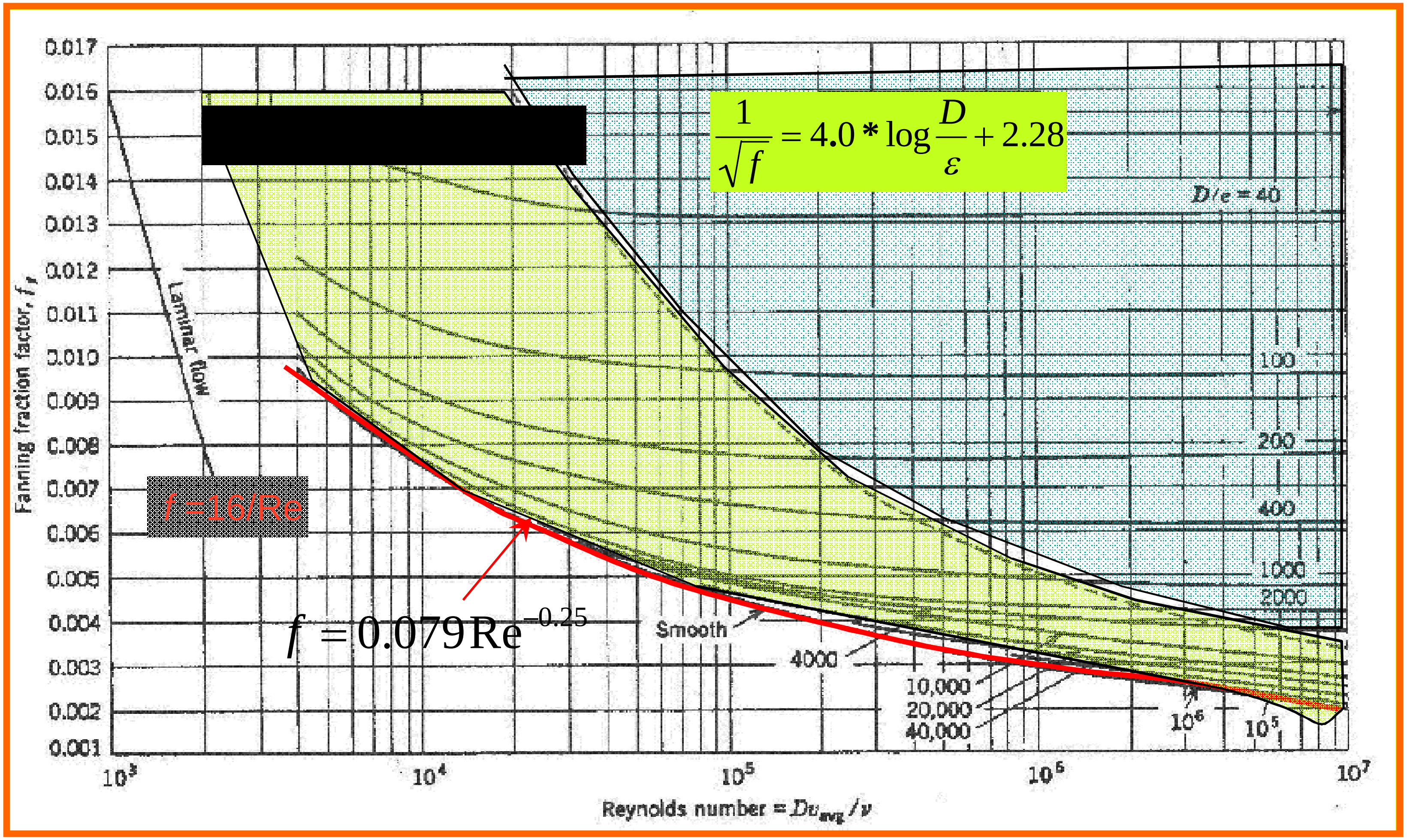
Rough pipe, [(D/ε)/(Re√ƒ) <0.01]

[redacted]

Transition function for both smooth and rough pipe

[redacted]

Fanning Diagram



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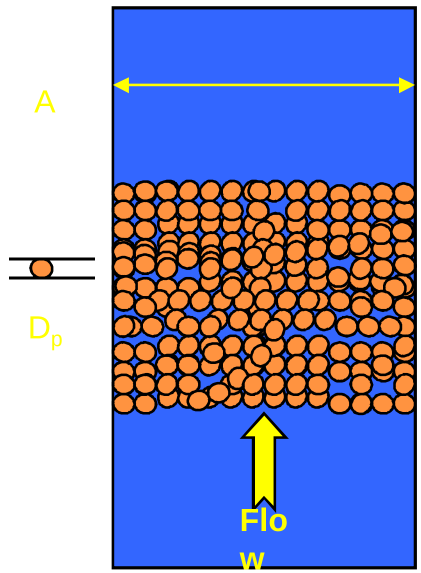
Pipe roughness

pipe material	pipe roughness ε (mm)
glass, drawn brass, copper	0.0015
commercial steel or wrought iron	0.045
asphalted cast iron	0.12
galvanized iron	0.15
cast iron	0.26
concrete	0.18-0.6
rivet steel	0.9-9.0
corrugated metal	45
PVC	0.12

Flow in a Packed pipe

The equations for empty pipe flow do not work with out considerable modification



Ergun Equation

[redacted]

D_p is the particle diameter,
ε is the volume fraction that is not occupied by particles

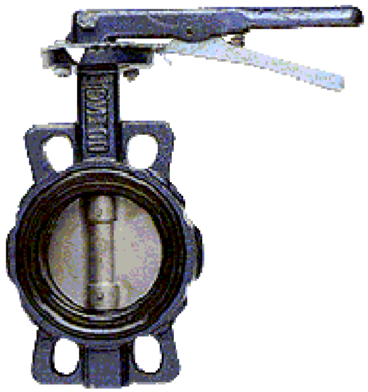
Reynolds number for a packed bed flow as

$$Re = \frac{U_o D_p \rho}{(1-\varepsilon)\mu}$$

This equation contains the interesting behavior that the pressure drop varies as the first power of U_o for small *Re* and as U_o^2 for higher *Re*.

Energy Loss in Valves

- Function of valve type and valve position
- The complex flow path through valves can result in high head loss (of course, one of the purposes of a valve is to create head loss when it is not fully open)
- E_v are the loss in terms of velocity heads



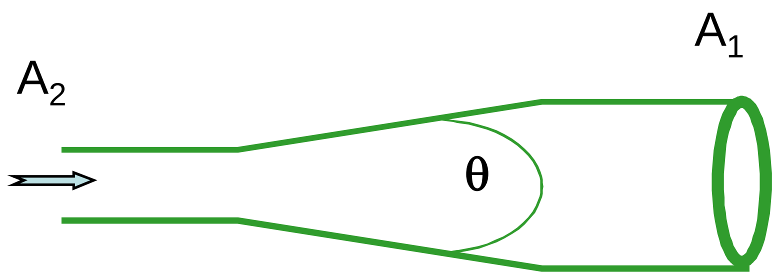
$$E_v = K\frac{U^2}{2}$$

$$h_v = \frac{\Delta p}{\rho} = K_v\frac{U^2}{2} = 2f\frac{L_{eq}}{D}\frac{U^2}{g}$$

Friction Loss Factors for valves

Valve	K	L_{eq}/D
Gate valve, wide open	0.15	7
Gate valve, 3/4 open	0.85	40
Gate valve, 1/2 open	4.4	200
Gate valve, 1/4 open	20	900
Globe valve, wide open	7.5	350

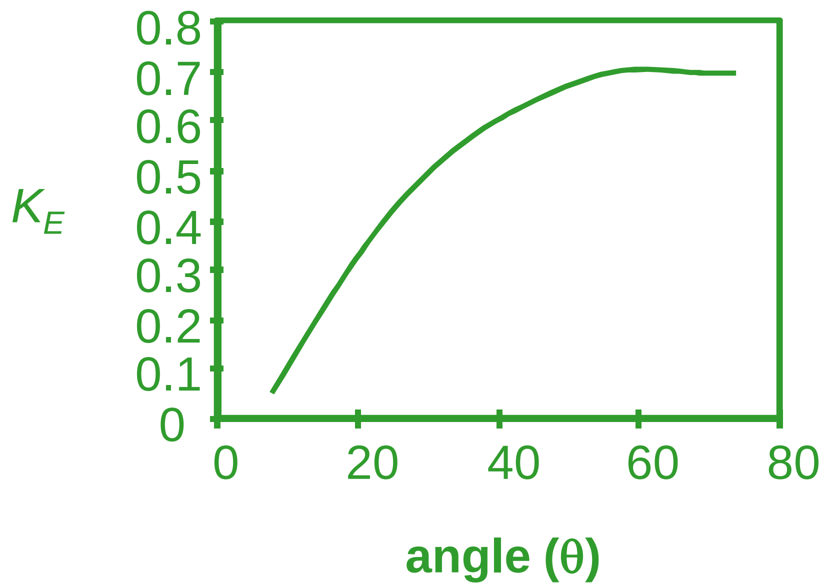
Energy Loss due to Gradual Expansion



$$E_E = K_E \frac{(U_1 - U_2)^2}{2}$$

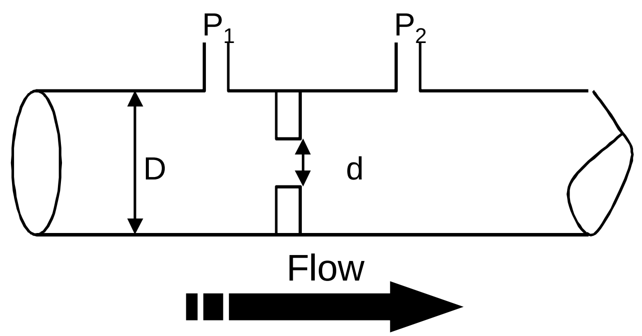
$$E_E = K_E \frac{U_2^2}{2} (\beta - 1)^2$$

$$\beta = \frac{A_2}{A_1}$$

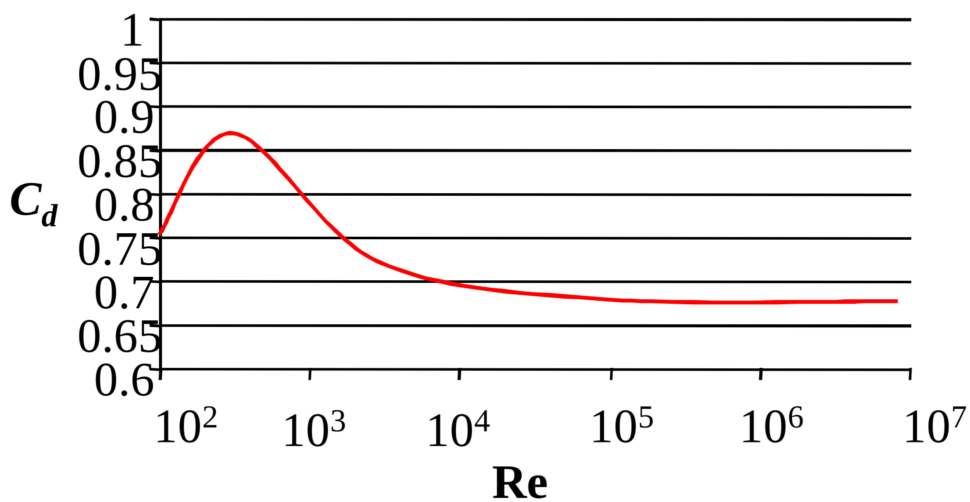


Sudden Contraction (Orifice Flowmeter)

Orifice flowmeters are used to determine a liquid or gas flowrate by measuring the differential pressure *P1-P2* across the orifice plate



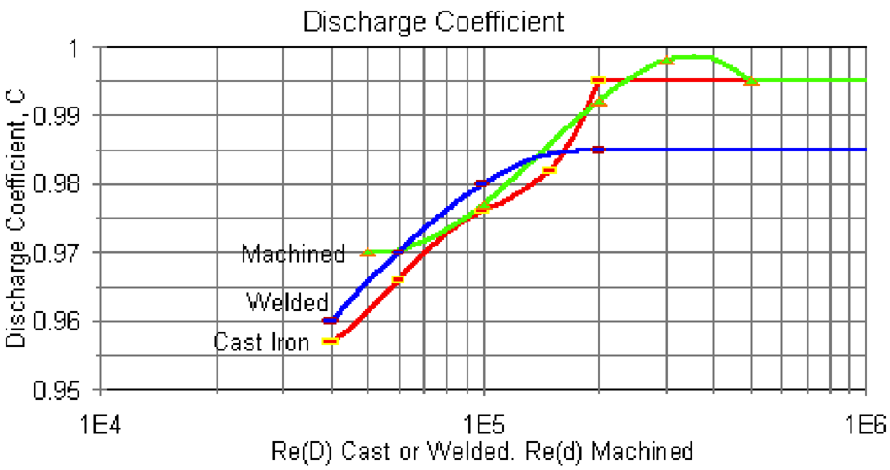
$$Q = C_d A_2 \left[\frac{2(p_1 - p_2)}{\rho(1-\beta^2)} \right]^{1/2}$$

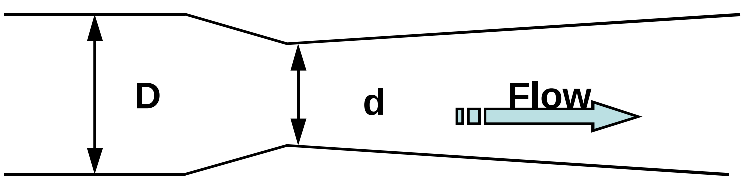


Reynolds number based on orifice diameter Re_d

Venturi Flowmeter

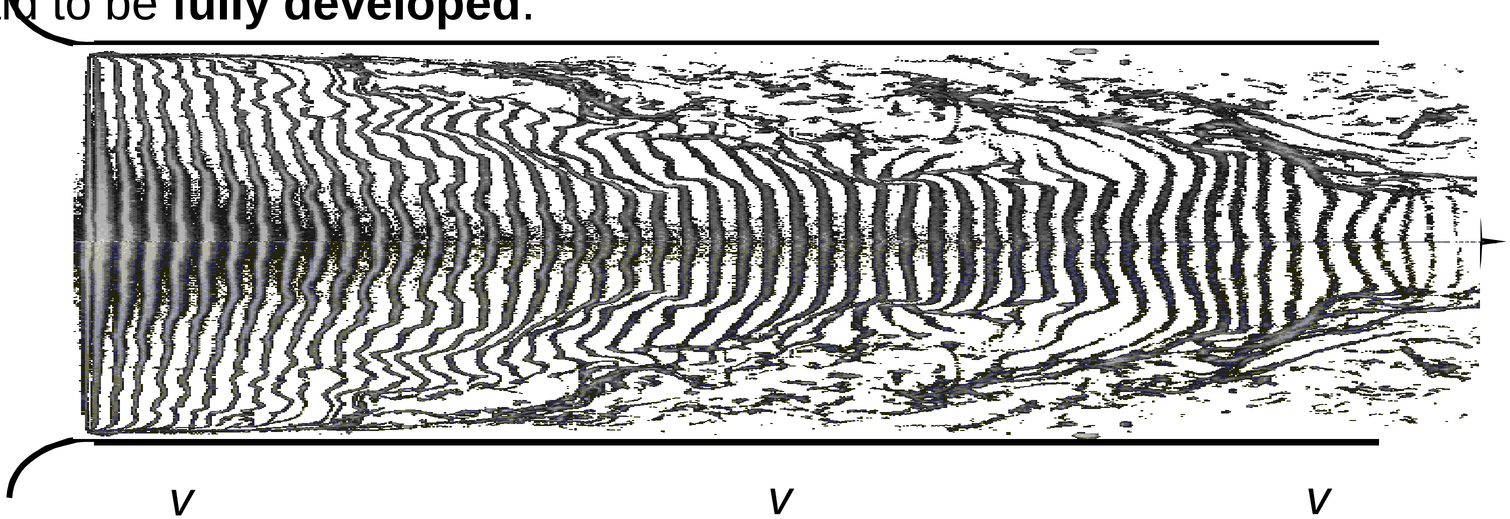
The classical Venturi tube (also known as the Herschel Venturi tube) is used to determine flowrate through a pipe. Differential pressure is the pressure difference between the pressure measured at D and at d





Boundary layer buildup in a pipe

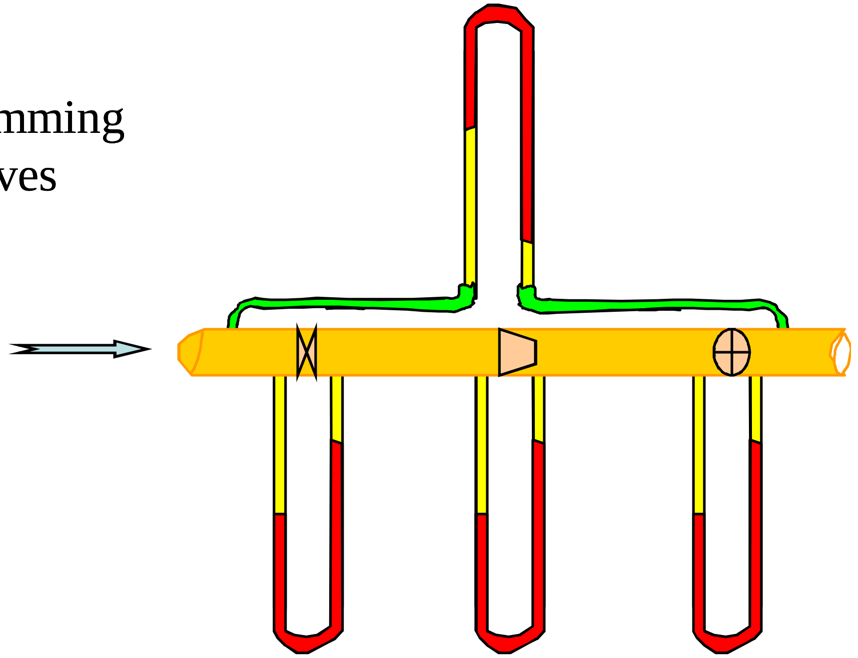
Because of the share force near the pipe wall, a boundary layer forms on the inside surface and occupies a large portion of the flow area as the distance downstream from the pipe entrance increase. At some value of this distance the boundary layer fills the flow area. The velocity profile becomes independent of the axis in the direction of flow, and the flow is said to be **fully developed**.



Pipe Flow Head Loss

(constant density fluid flows)

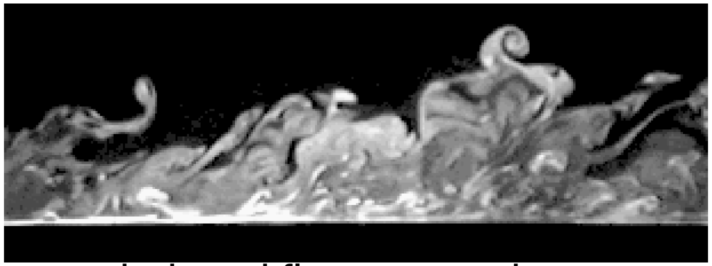
- Pipe flow head loss is
- proportional to the length of the pipe
- proportional to the square of the velocity (high Reynolds number)
- Proportional inversely with the diameter of the pipe
- increasing with surface roughness
- independent of pressure
- Total losses in the pipe system is obtained by summing individual head losses of roughness, fittings, valves ..itc



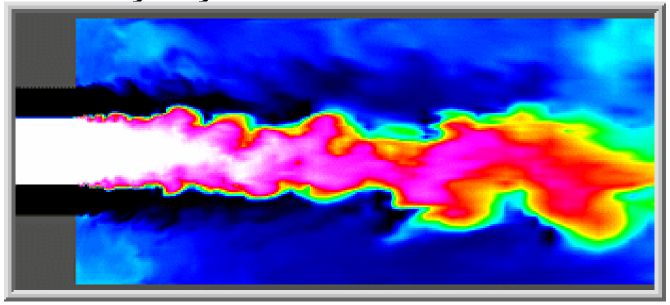
Pipe Flow Summary

- **The statement of conservation of mass, momentum and energy becomes the Bernoulli equation for steady state constant density of flows.**
- **Dimensional analysis gives the relation between flow rate and pressure drop.**
- **Laminar flow losses and velocity distributions can be derived based on momentum and mass conservation to obtain exact solution named of Hagen - Poisuille**
- **Turbulent flow losses and velocity distributions require experimental results.**
- **Experiments give the relationship between the fraction factor and the Reynolds number.**
- **Head loss becomes minor when fluid flows at high flow rate (fraction factor is constant at high Reynolds numbers).**

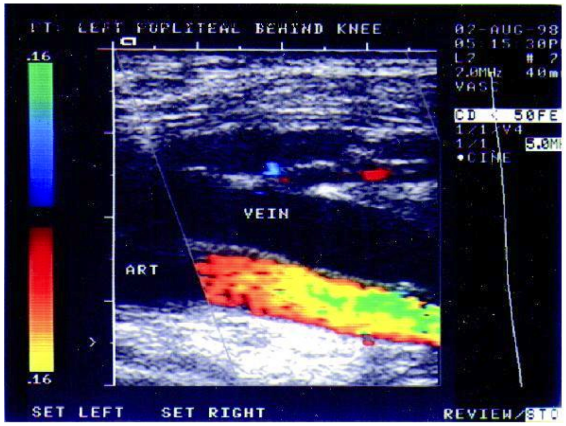
Images - Laminar/Turbulent Flows



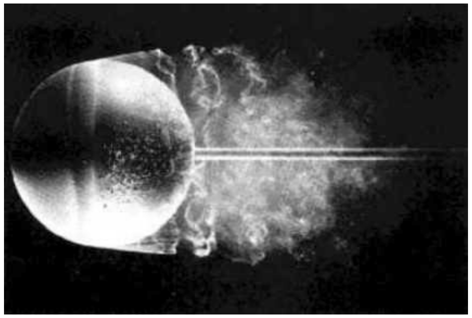
Laser - induced florescence image of an incompressible turbulent boundary layer



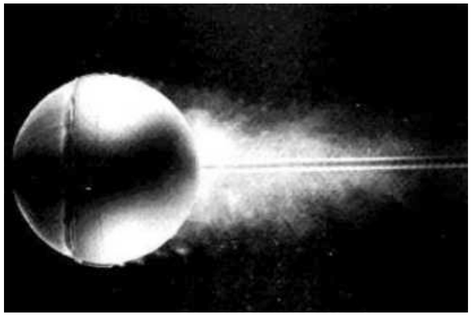
Simulation of turbulent flow coming out of a tailpipe



Laminar flow (



Turbulent flow



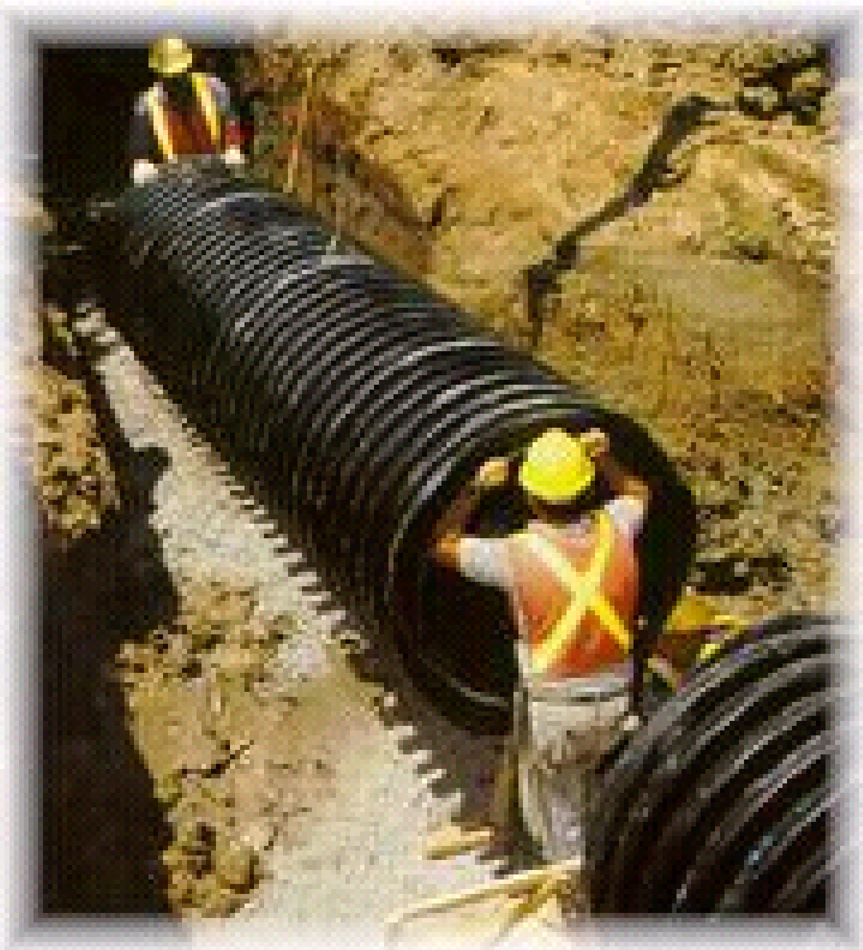
Laminar flow

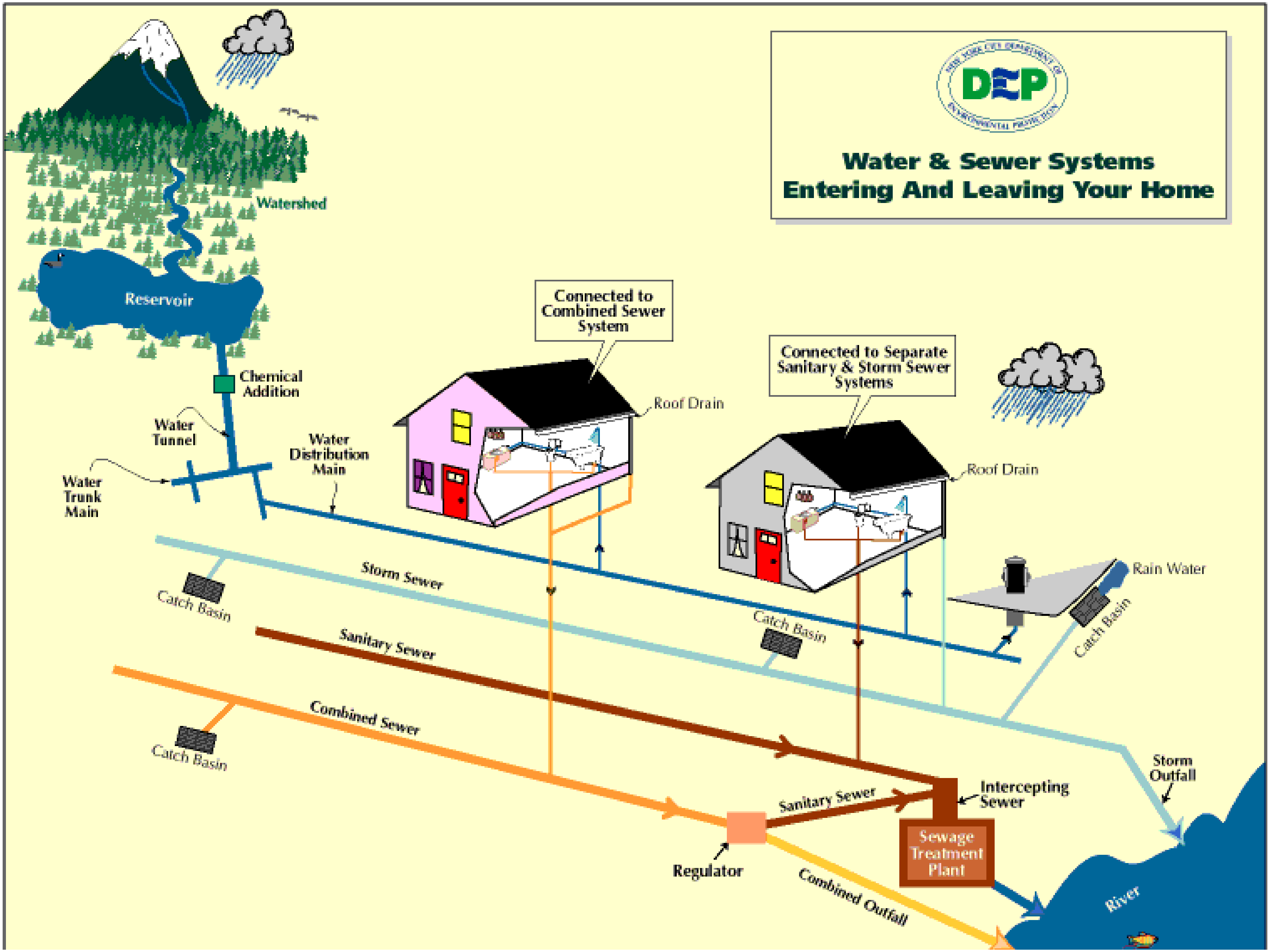
http://www.engineering.uiowa.edu/~cfd/gallery/lim-turb.html

Pipes are Everywhere!

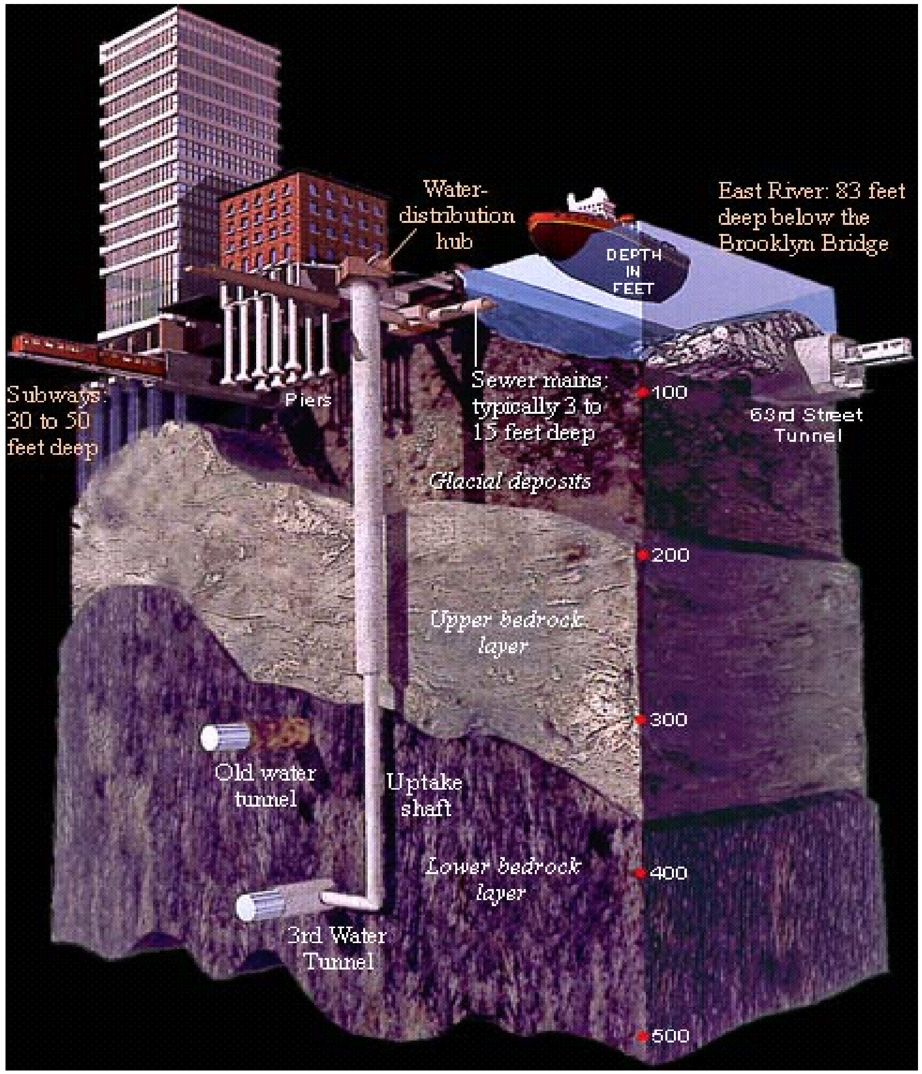
Owner: **City of Hammond, IN**
Project: **Water Main Relocation**
Pipe Size: **54"**

Pipes are Everywhere! Drainage Pipes




DEP
Water & Sewer Systems
Entering And Leaving Your Home
Watershed
Reservoir
Chemical Addition
Water Tunnel
Water Trunk Main
Water Distribution Main
Connected to Combined Sewer System
Roof Drain
Connected to Separate Sanitary & Storm Sewer Systems
Roof Drain
Rain Water
Storm Sewer
Catch Basin
Catch Basin
Catch Basin
Sanitary Sewer
Combined Sewer
Catch Basin
Storm Outfall
Intercepting Sewer
Sanitary Sewer
Regulator
Sewage Treatment Plant
Combined Outfall
River

Pipes are Everywhere! Water Mains

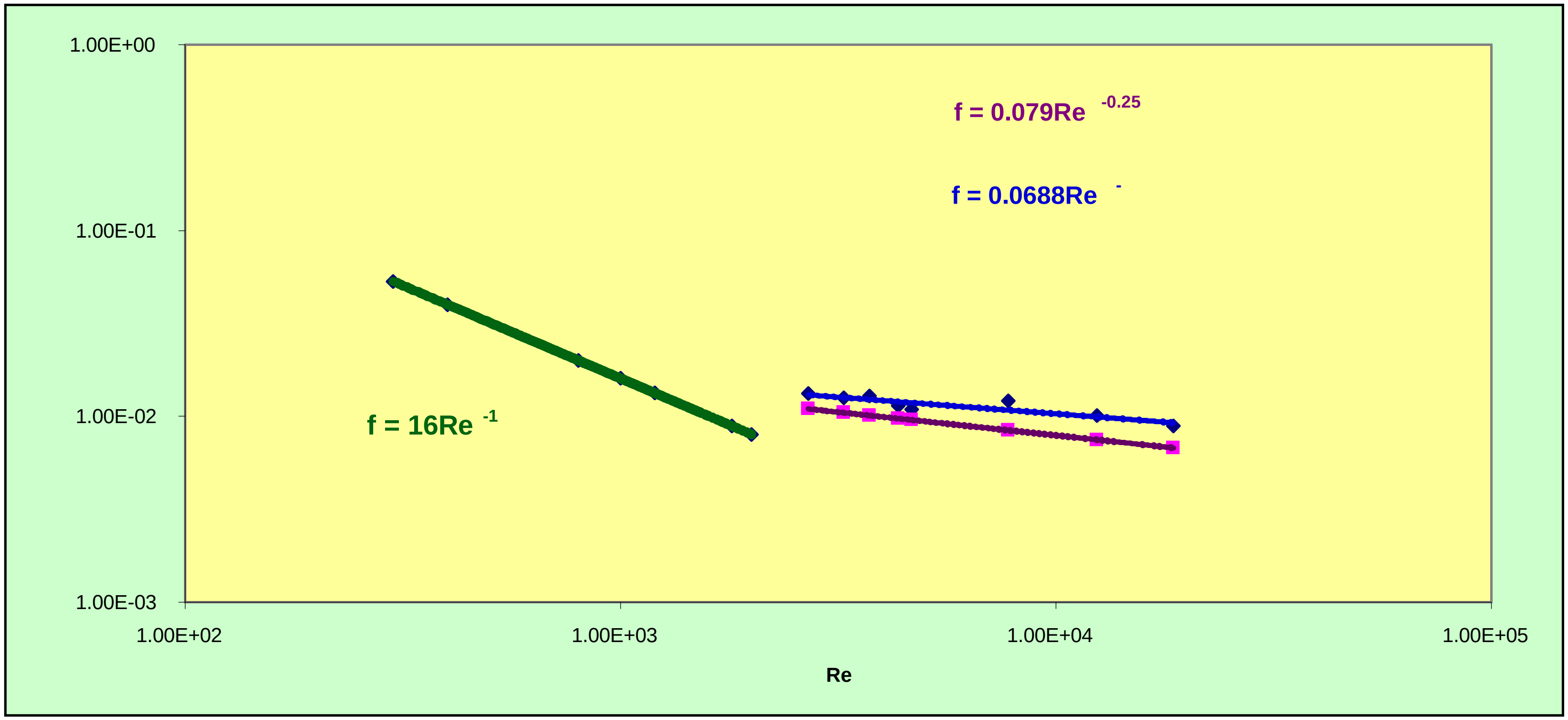


D (m)	area (m)^2	Flowrate (cc/min)	Flowrate (cc/sec)	Flowrate m^3/sec	velosity (m/sec)	Re	Presure (in(water)	Presure (m	Presure d Pa(N/M2)	DP/L	Friction f exp (P:	Friction f equ	Fa
0.0068326	3.66806E-05	300	5	0.000005	0.1363118	9.31E+02	0.80	2.00E-02	196.0000	1.05E+02	0.01980	0.01430	
0.0068326	3.66806E-05	600	10	0.00001	0.2726235	1.86E+03	1.90	4.75E-02	465.5000	2.50E+02	0.01176	0.01203	
0.0068326	3.66806E-05	870	14.5	0.0000145	0.3953041	2.70E+03	4.50	1.13E-01	1102.5000	5.93E+02	0.01324	0.01096	
0.0068326	3.66806E-05	1050	17.5	0.0000175	0.4770912	3.26E+03	6.22	1.58E-01	1523.9000	8.19E+02	0.01257	0.01046	
0.0068326	3.66806E-05	1200	20	0.00002	0.5452471	3.73E+03	8.30	2.08E-01	2033.5000	1.09E+03	0.01284	0.01011	
0.0068326	3.66806E-05	1400	23.333333	2.333E-05	0.6361216	4.35E+03	10.00	2.50E-01	2450.0000	1.32E+03	0.01137	0.00973	
0.0068326	3.66806E-05	1500	25	0.000025	0.6815589	4.66E+03	11.00	2.75E-01	2695.0000	1.45E+03	0.01089	0.00956	
0.0068326	3.66806E-05	2500	41.666667	4.167E-05	1.1359314	7.76E+03	34.00	8.50E-01	8330.0000	4.48E+03	0.01212	0.00842	
0.0068326	3.66806E-05	4000	66.666667	6.667E-05	1.8174903	1.24E+04	72.30	1.81E+00	17713.5000	9.52E+03	0.01007	0.00748	
0.0068326	3.66806E-05	6000	100	0.0001	2.7262354	1.86E+04	143.00	3.58E+00	35035.0000	1.88E+04	0.00885	0.00676	

$$\Delta P = h_{mano.reading} * (\rho_{liquid} - \rho_{water}) * g$$

$$Re = \frac{\rho \; DV}{\mu}$$

$$f = \frac{\Delta \; P}{L} \frac{D}{2 \; \rho \; U^{2}}$$


1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E+02
1.00E+03
1.00E+04
1.00E+05
Re
f = 0.079Re -0.25
f = 0.0688Re -
f = 16Re -1

Dimensional Analysis

- Units are meters, seconds, feet, tons, etc.
- Types of units are length, mass, force, volume, etc.
- The type of unit of a value is called the dimension.
  - A value in square meters has dimensions of an area.
  - A value in kilometers per hour has dimensions of a velocity.

Units and Types

- It is useful to convert the dimensions of units into fundamental dimensions.
  - Length (L)
  - Time (T)
  - Mass (M)
- Units can be raised to a power, and so can the fundamental dimensions.
  - Area (L^2)
  - Volume (L^3)
  - Force ($M L / T^2$)

Powers of Units

Dimensional Expressions

- The speed of waves in shallow water depends only on the acceleration of gravity *g*, with dimensions L/T^2, and on the water depth *h*. Which of the following formulas for the wave speed *v* could be correct?

a) $v = \frac{1}{2} g h^2$

b) $v = \sqrt{gh}$

Base Quantities

Acceleration *g*

- dimensions: L/T^2
- length/time^2
- example: m/s^2

Height *h*

- dimensions: L
- length
- example cm

Speed *v*

- dimensions: L/T
- length/time
- example km/h

Checking a Result

$$v = \frac{1}{2} g h^2$$

$$\frac{L}{T} = \frac{L}{T^2} L^2$$

- Terms do not match

$$\frac{L}{T} = \frac{L^3}{T^2}$$

$$v = \sqrt{gh}$$

$$\frac{L}{T} = \sqrt{\frac{L}{T^2} L}$$

- Terms match, this could be a valid formula.

$$\frac{L}{T} = \frac{L}{T}$$

Limitations

- Dimensional analysis only checks the units.
- Numeric factors have no units and can't be tested.

$$v = \frac{\sqrt{gh}}{3}$$

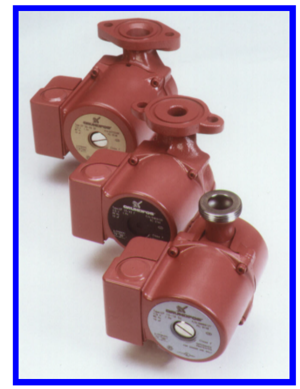
is also valid.

$$v = \sqrt{gh} + 4$$

is not valid.

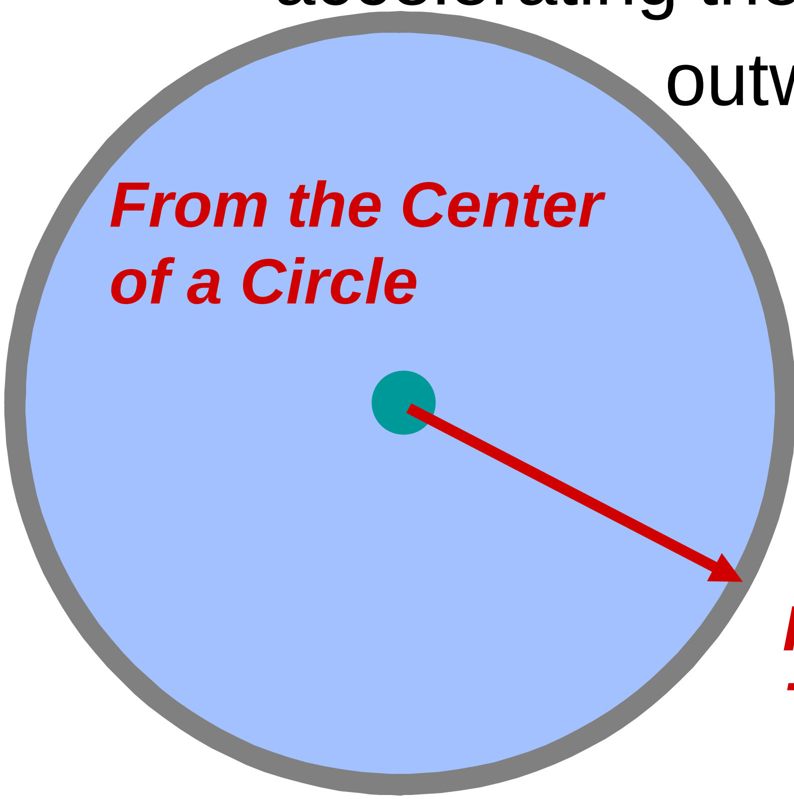
next


GRUNDFOS
GRUNDFOS
GRUNDFOS



Centrifugal Pumps

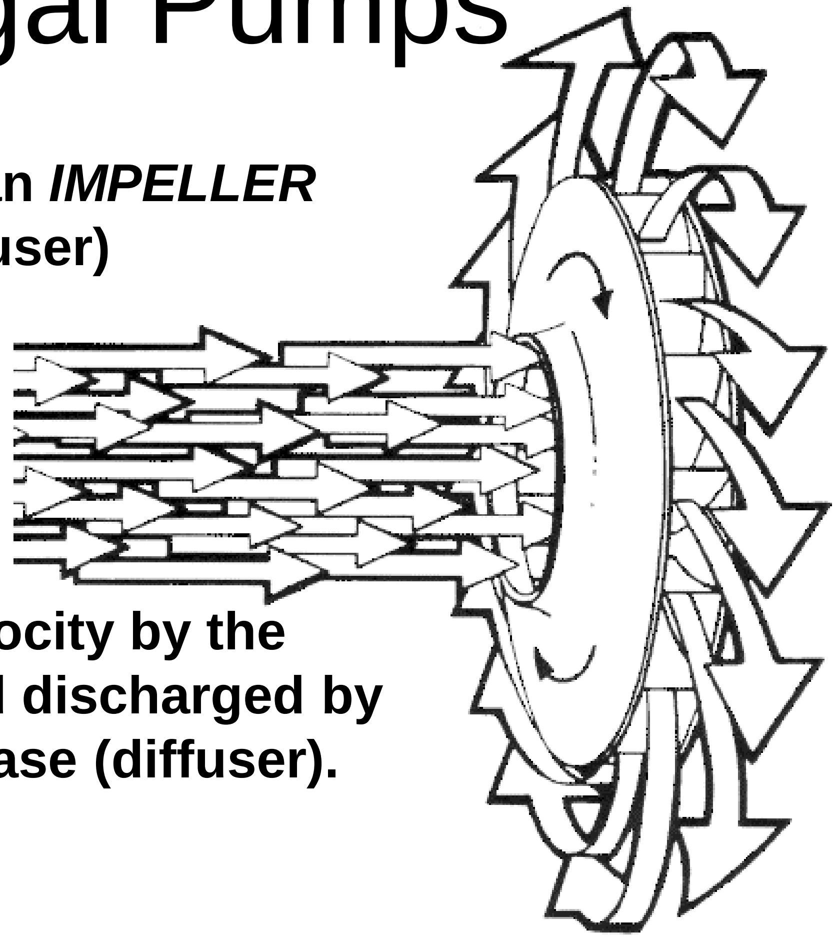
A machine for moving fluid by accelerating the fluid *RADIALLY* outward.



Centrifugal Pumps

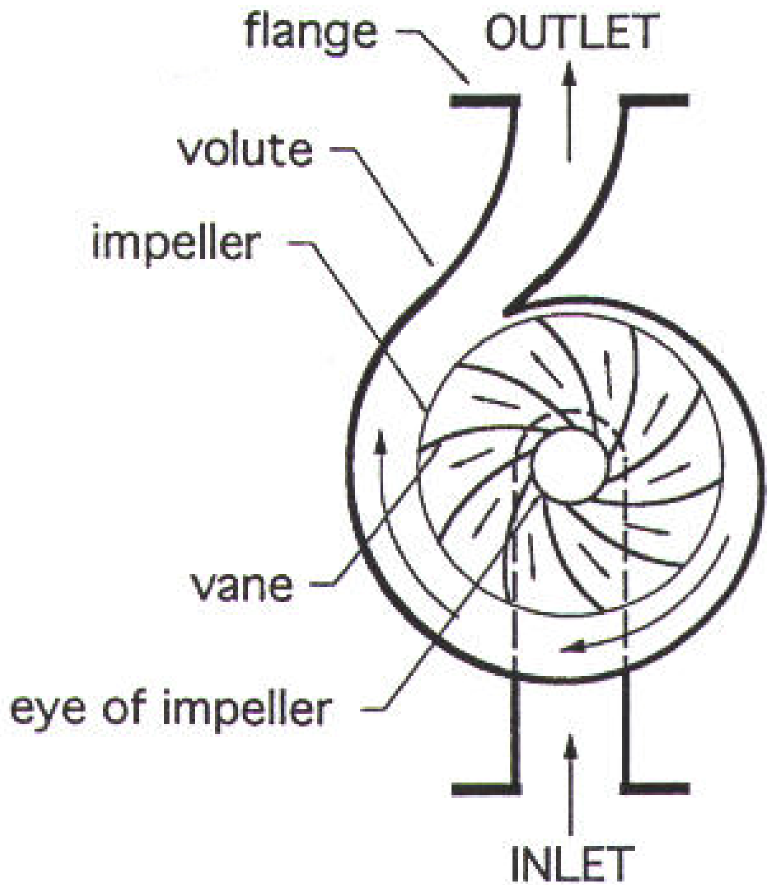
- **This machine consists of an *IMPELLER* rotating within a case (diffuser)**

- **Liquid directed into the center of the rotating impeller is picked up by the impeller's vanes and accelerated to a higher velocity by the rotation of the impeller and discharged by centrifugal force into the case (diffuser).**



Centrifugal Pumps

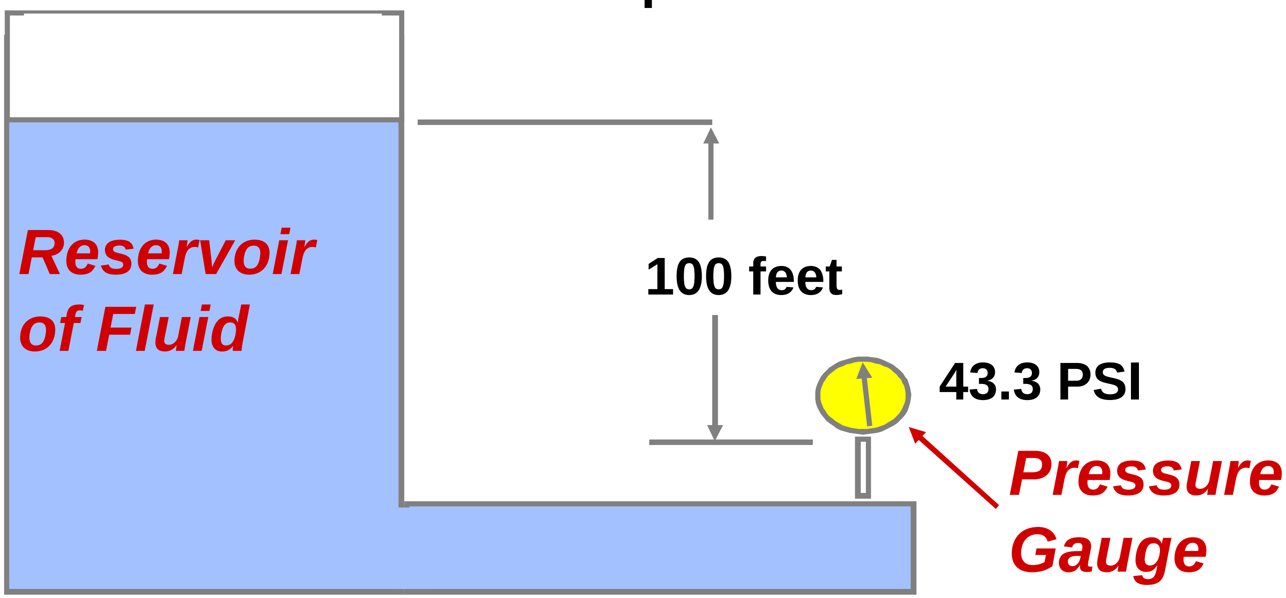
- A collection chamber in the casing converts much of the Kinetic Energy (energy due to velocity) into *Head* or Pressure.



Pump Terminology

"Head"

- **Head is a term for expressing feet of water column**
- **Head can also be converted to pressure**



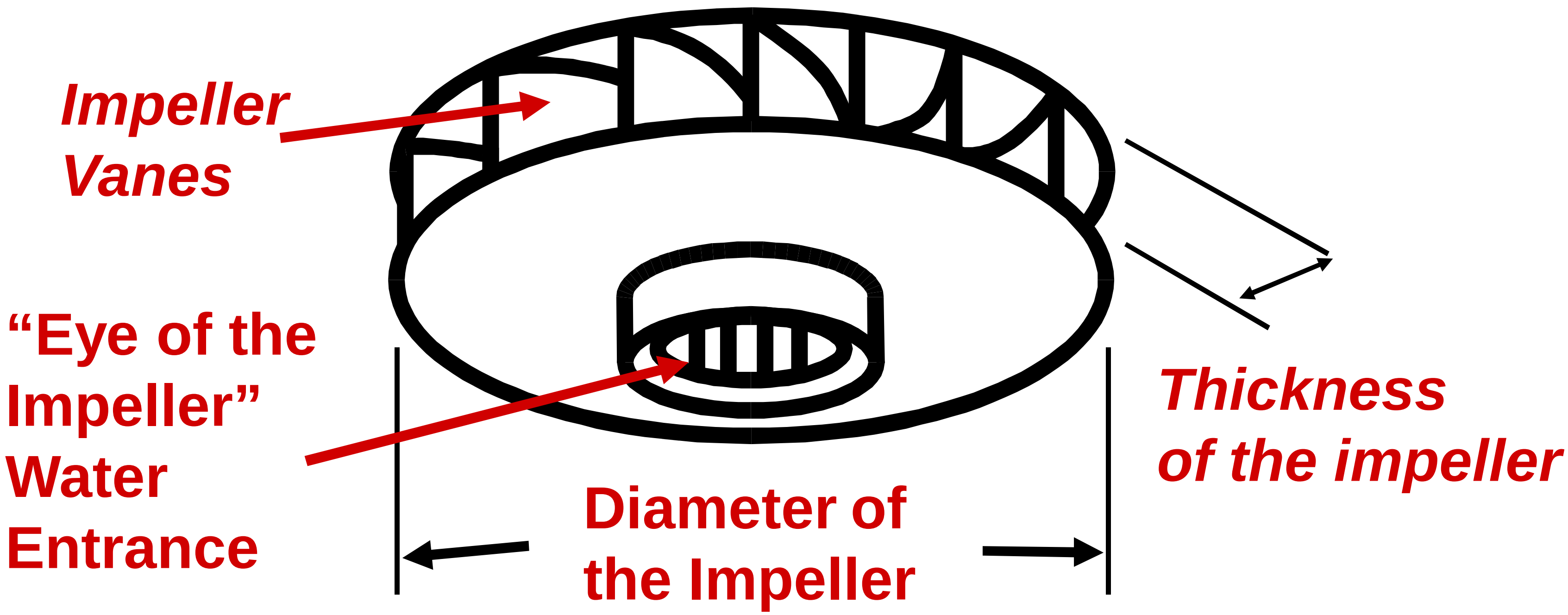
Conversion Factors Between Head and Pressure

- **Head (feet of liquid) =Pressure in PSI x 2.31 / Sp. Gr.**
- **Pressure in PSI = Head (in feet) x Sp. Gr. / 2.31**
- **PSI is Pounds per Square Inch**
- **Sp. Gr. is Specific Gravity which for water is equal to 1**
  - **For a fluid more dense than water, Sp. Gr. is greater than 1**
  - **For a fluid less dense than water, Sp. Gr. is less than 1**

Head

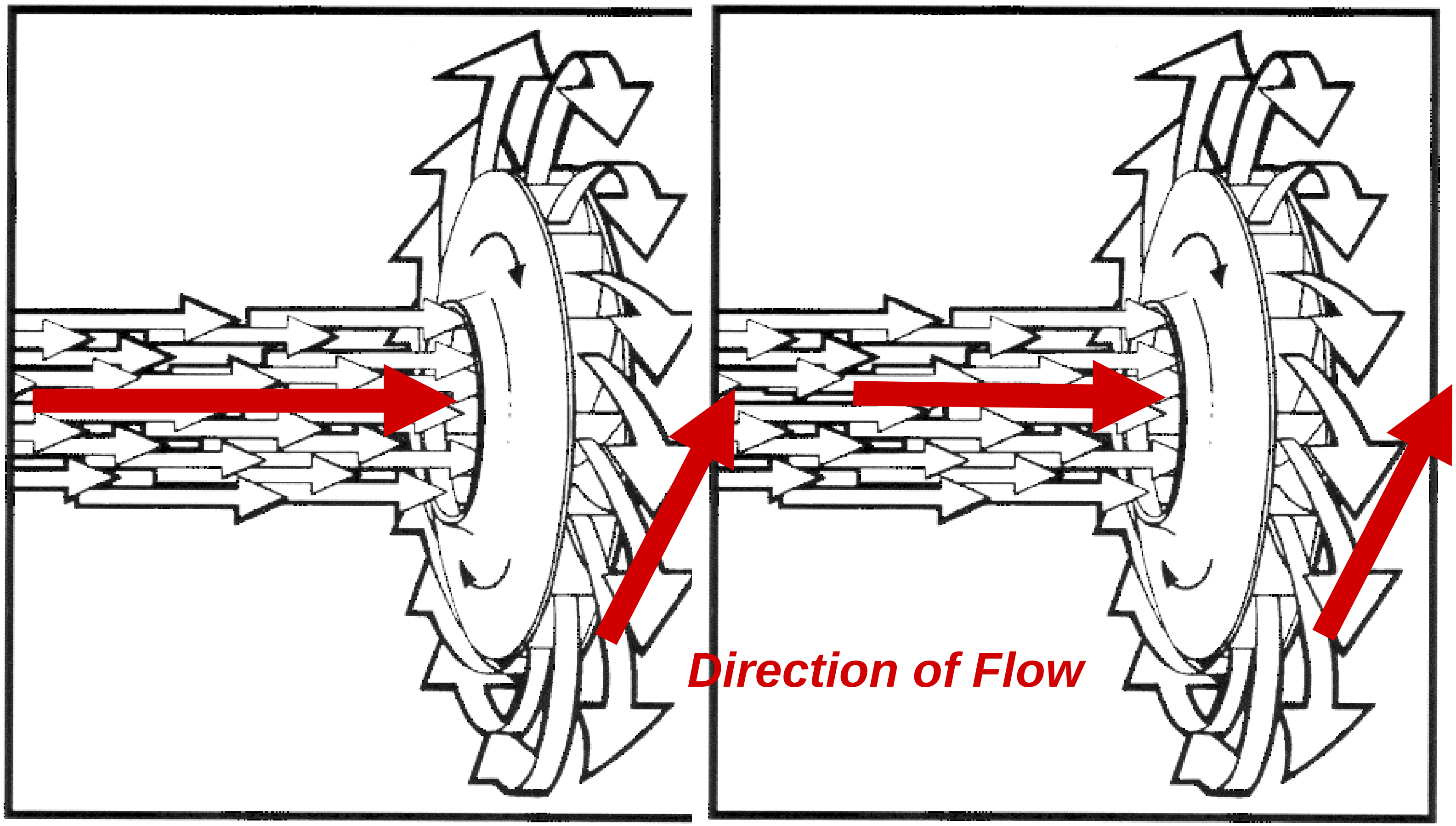
- Head and pressure are interchangeable terms provided that they are expressed in their correct units.
- The conversion of all pressure terms into units of equivalent head simplifies most pump calculations.

Centrifugal Impellers



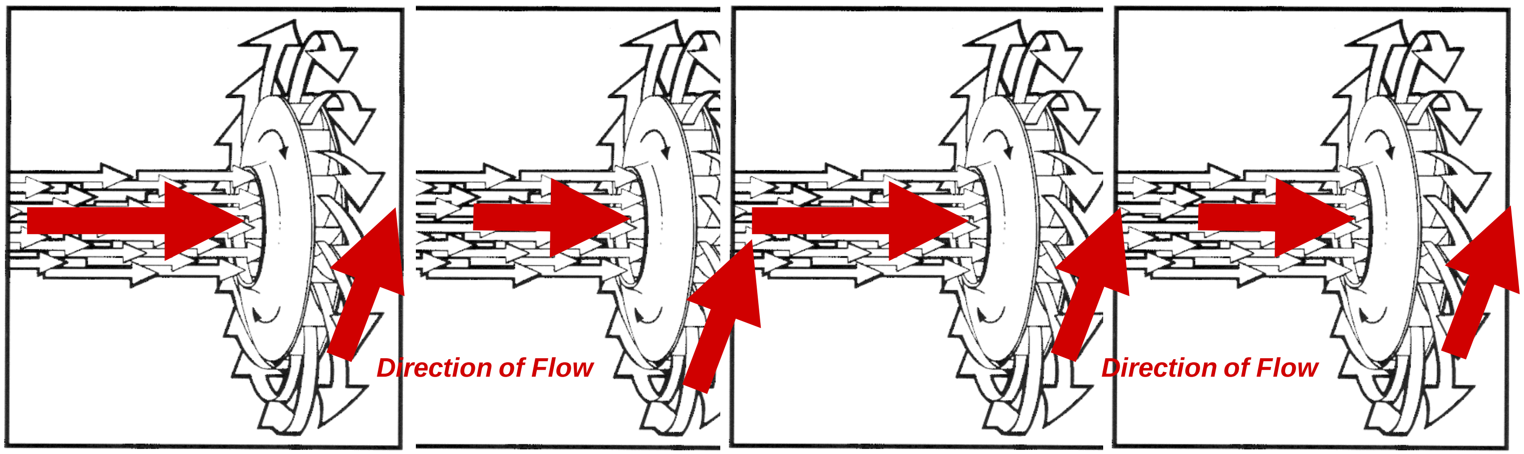
- Thicker the Impeller- More Water
- Larger the DIAMETER - More Pressure
- Increase the Speed - More Water and Pressure

Two Impellers in Series



- Twice the pressure
- Same amount of water

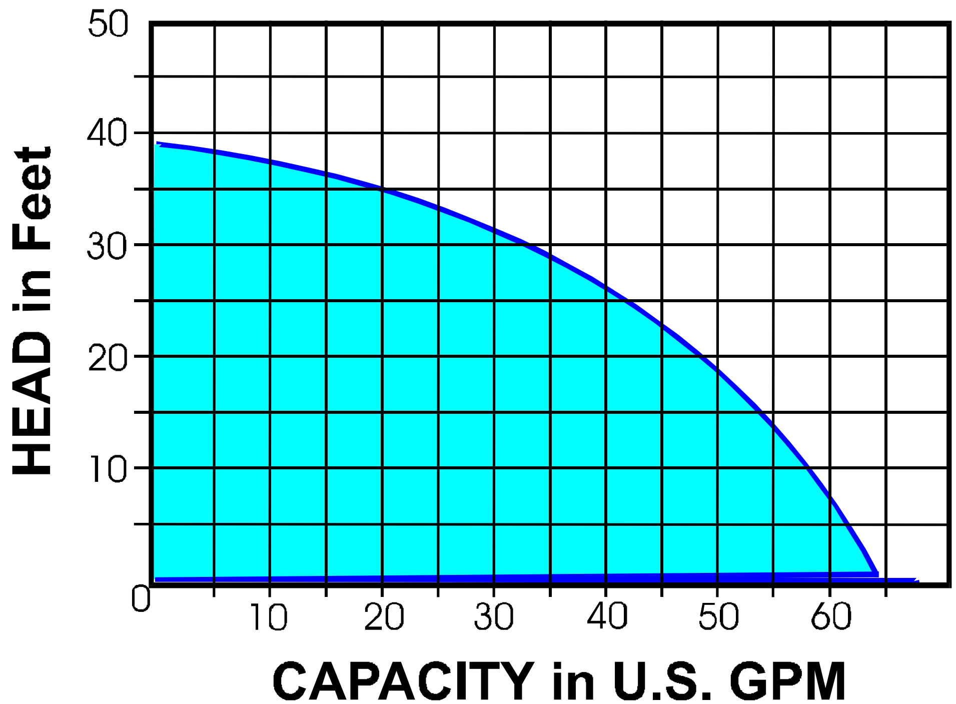
Multiple Impellers in Series



- Placing impellers in series increases the amount of head produced
- The head produced = # of impellers x head of one impeller

Pump Performance Curve

- **A mapping or graphing of the pump's ability to produce head and flow**



Pump Performance Curve

Step #1, Horizontal Axis

- The pump's flow rate is plotted on the horizontal axis (X axis)
- Usually expressed in Gallons per Minute

Pump Flow Rate →

Pump Performance Curve

Step #2, Vertical Axis

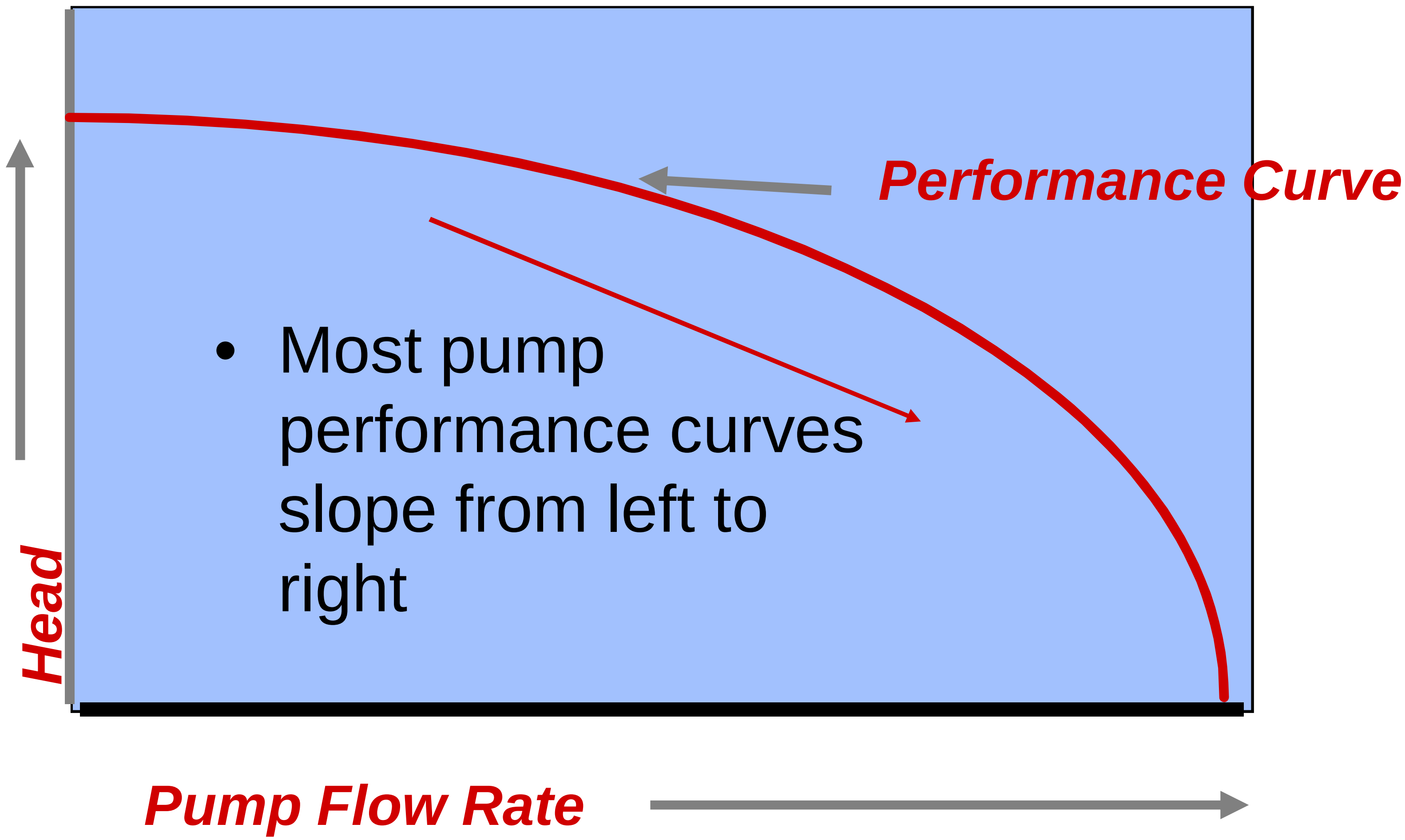
- The head the pump produces is plotted on the vertical axis (Y axis)
- Usually express in Feet of Water

Head

Pump Flow Rate

Pump Performance Curve

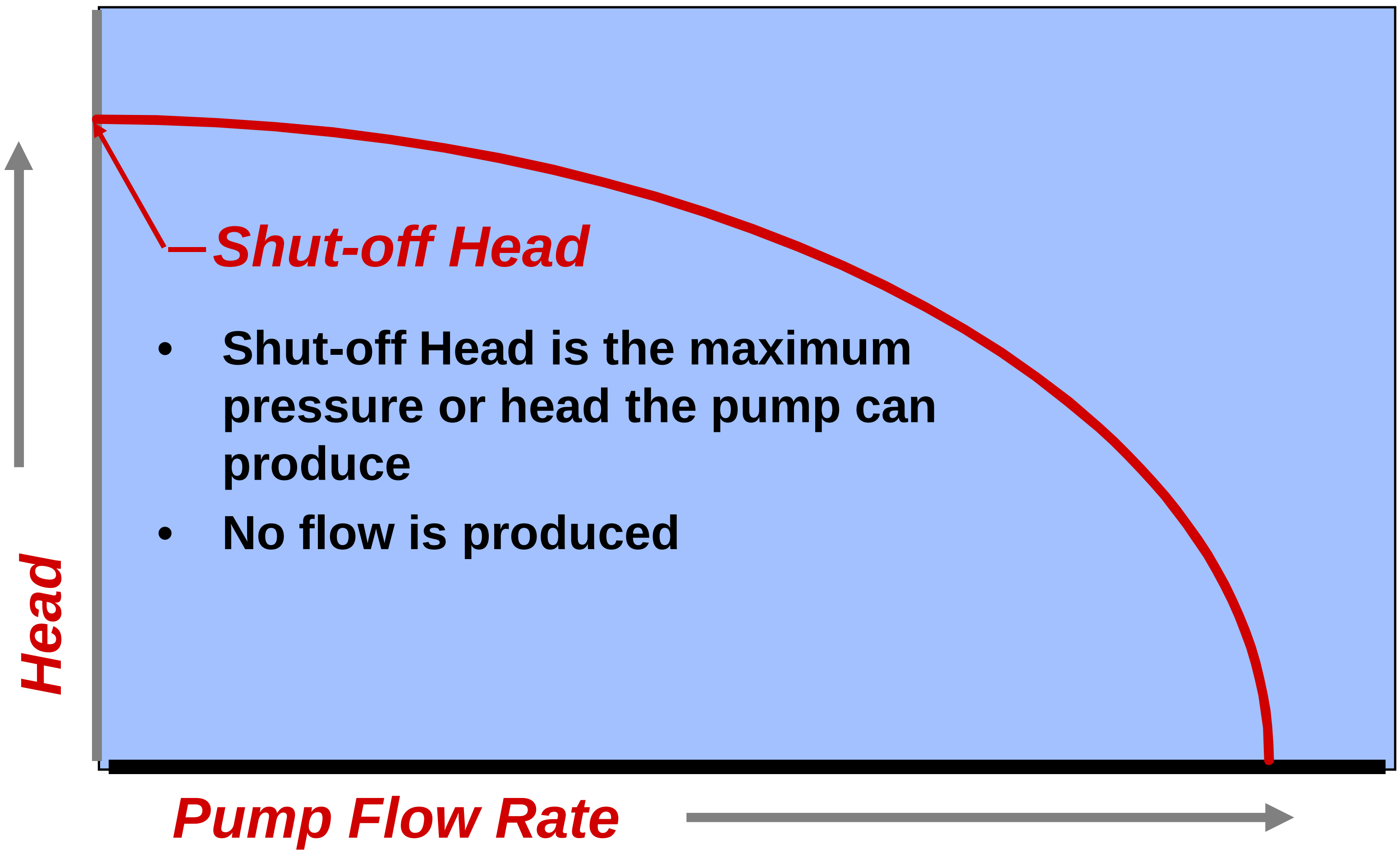
Step #3, Mapping the Flow and the Head



- Most pump performance curves slope from left to right

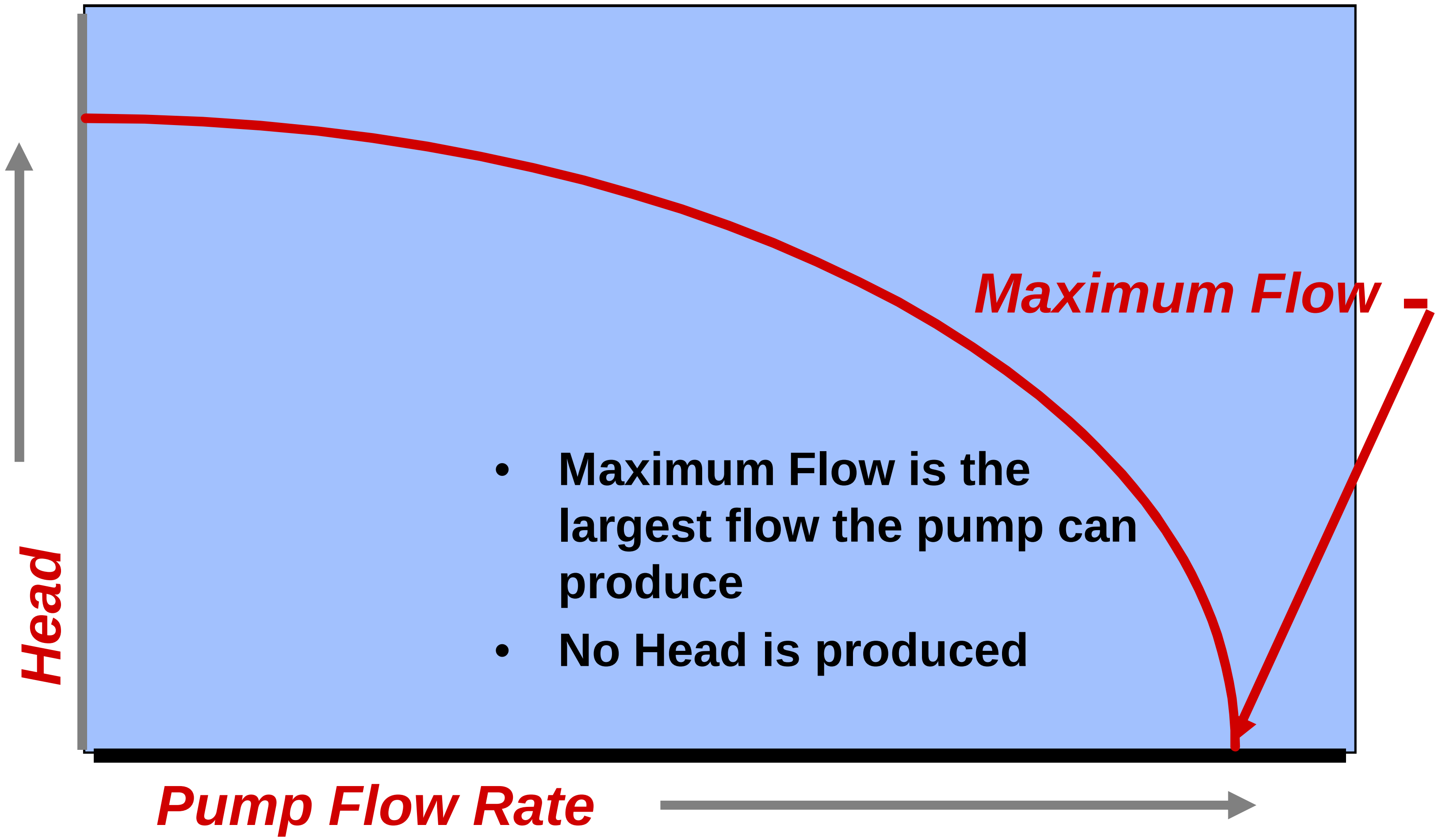
Pump Performance Curve

Important Points



Pump Performance Curve

Important Points



- **Maximum Flow is the largest flow the pump can produce**
- **No Head is produced**

System Performance Curves

- System Performance Curve is a mapping of the head required to produce flow in a given system
- A system includes all the pipe, fittings and devices the fluid must flow through, and represents the friction loss the fluid experiences

System Performance Curve

Step #1, Horizontal Axis

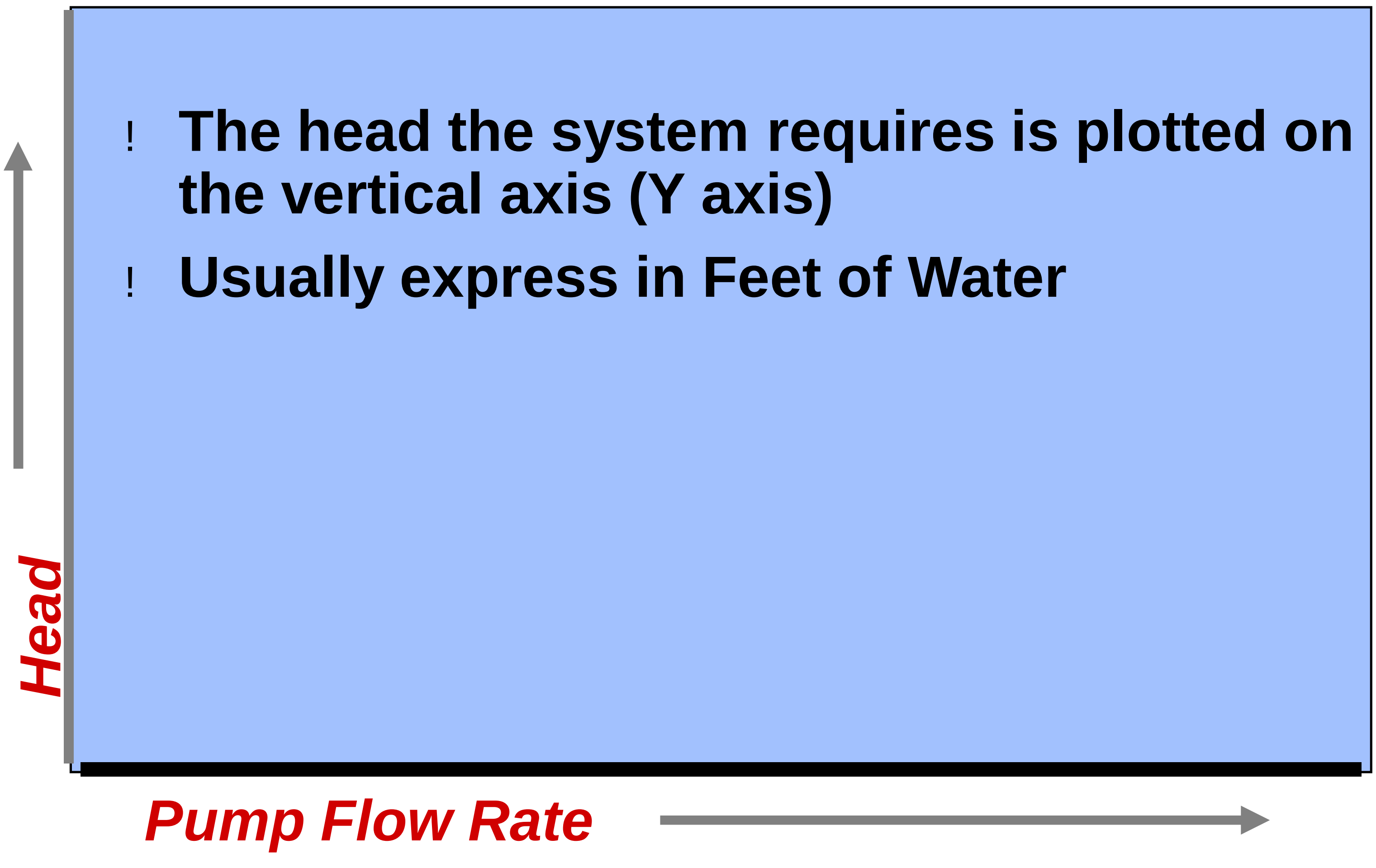
- **The System's flow rate in plotted on the horizontal axis (X axis)**
- **Usually expressed in Gallons per Minute**

System Flow Rate →

System Performance Curve

Step #2, Vertical Axis

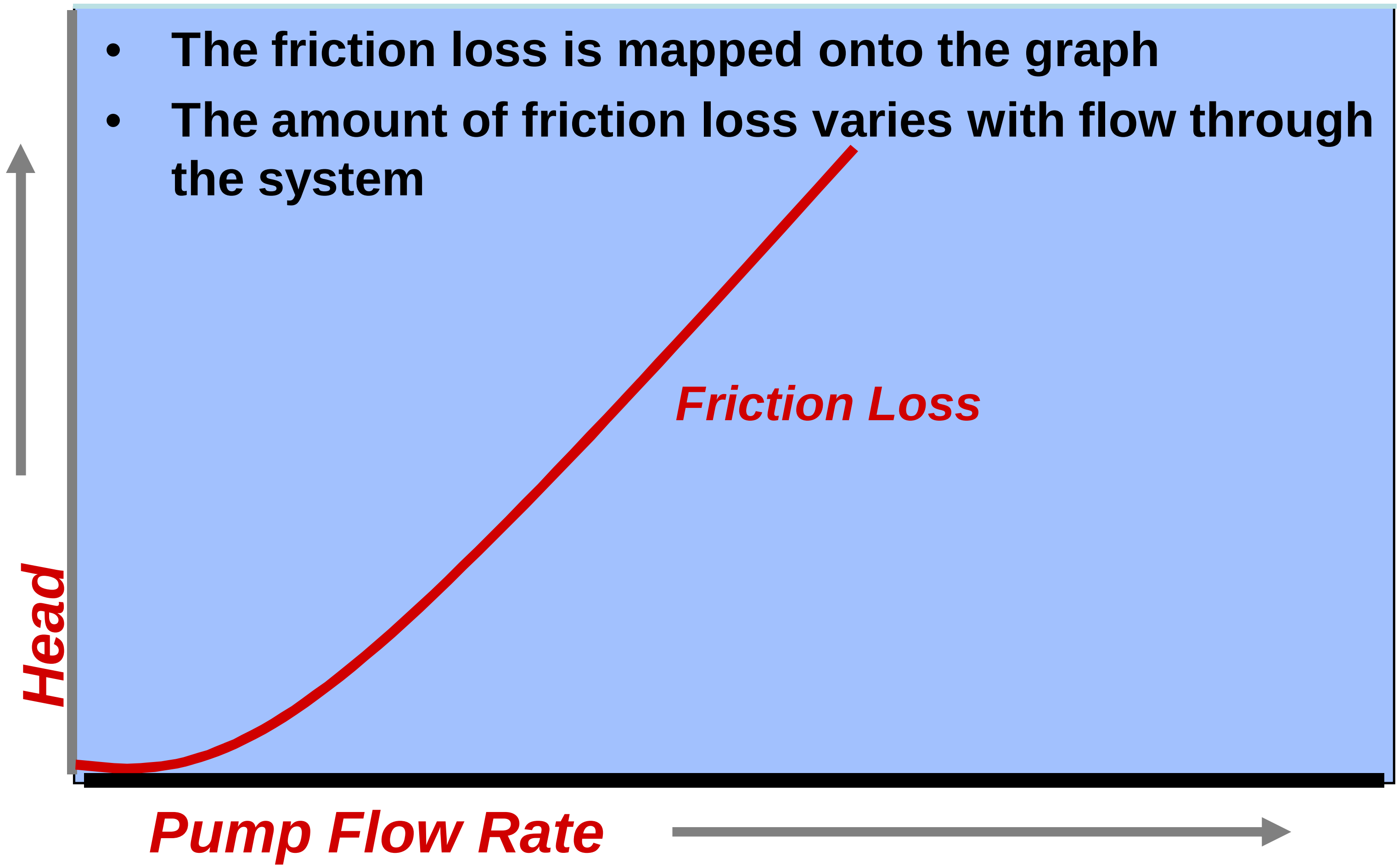
- **The head the system requires is plotted on the vertical axis (Y axis)**
- **Usually express in Feet of Water**



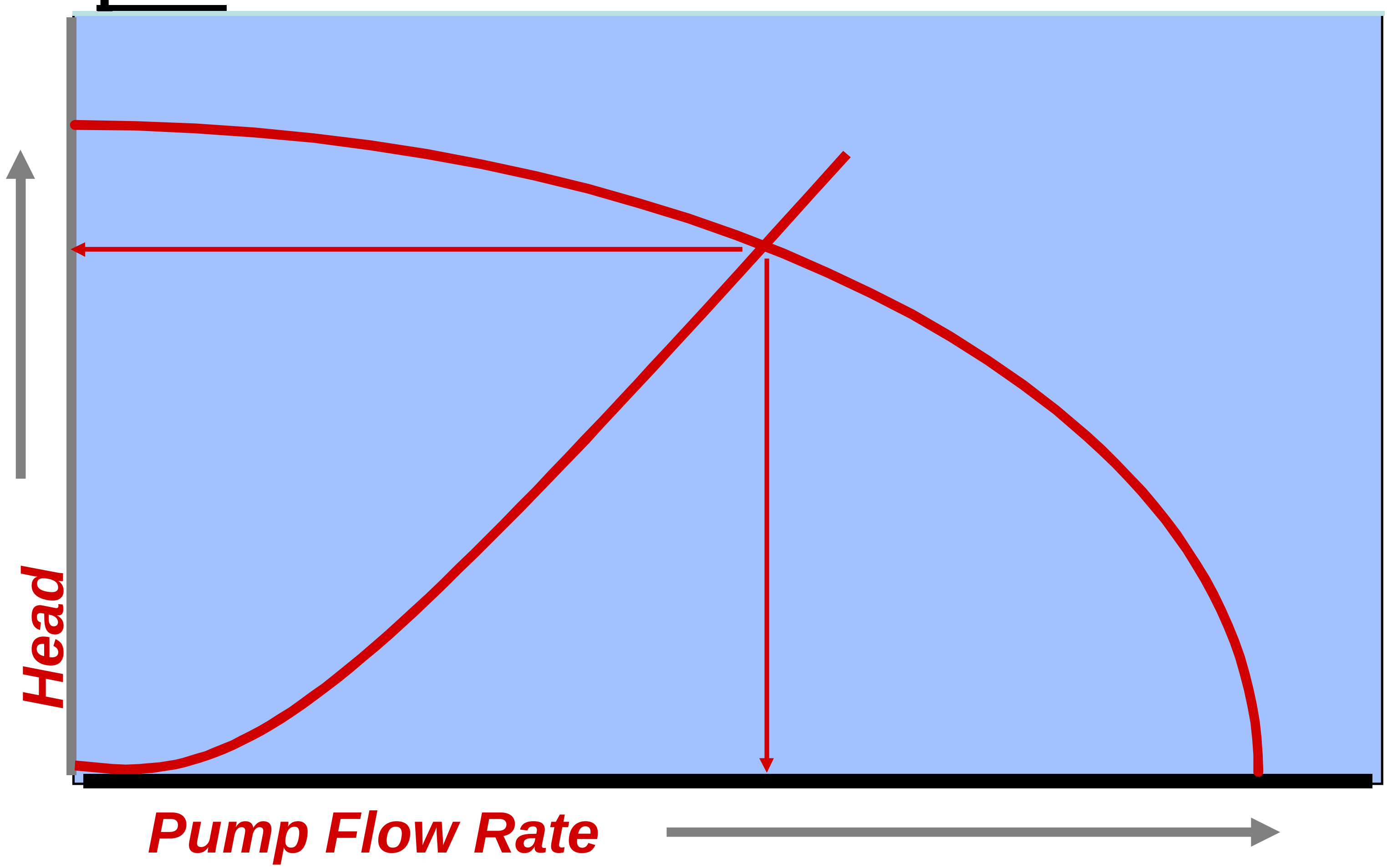
System Performance Curve

Step #3, Curve Mapping

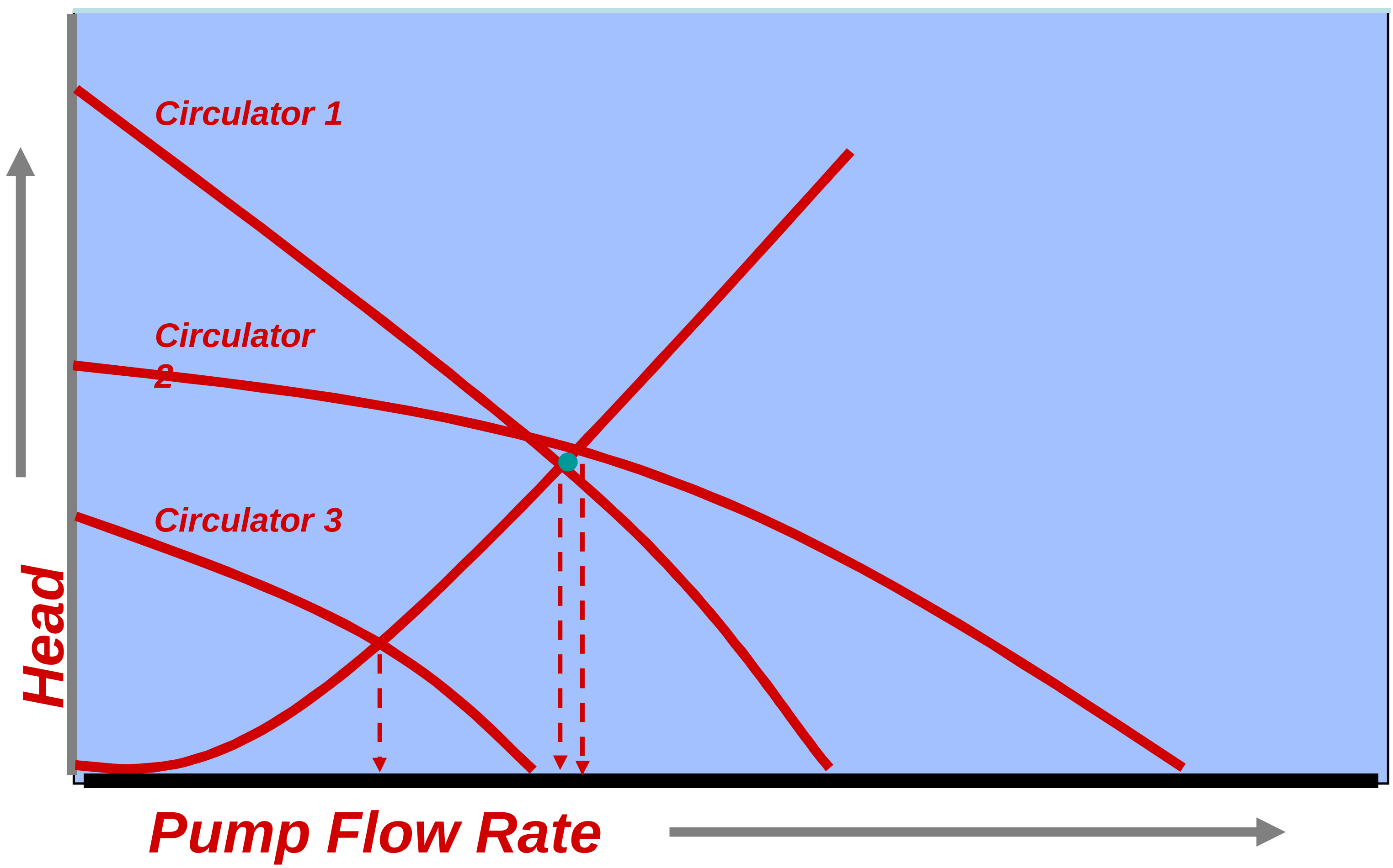
- **The friction loss is mapped onto the graph**
- **The amount of friction loss varies with flow through the system**



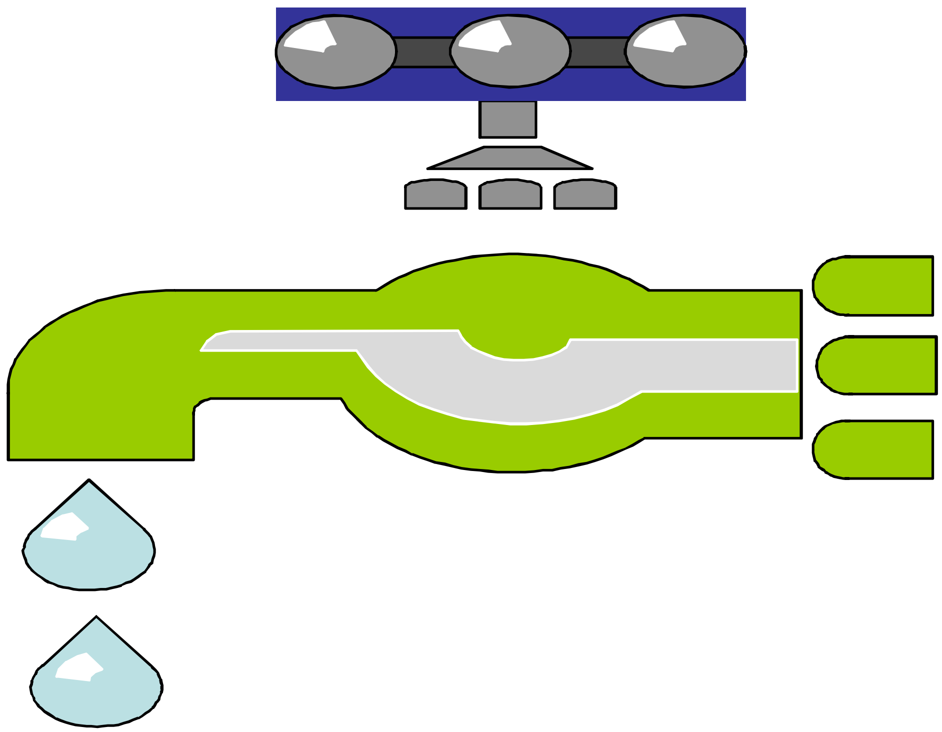
The point on the system curve that intersects the pump curve is known as the <u>operating point</u>.



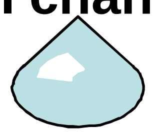
PUMP SELECTION



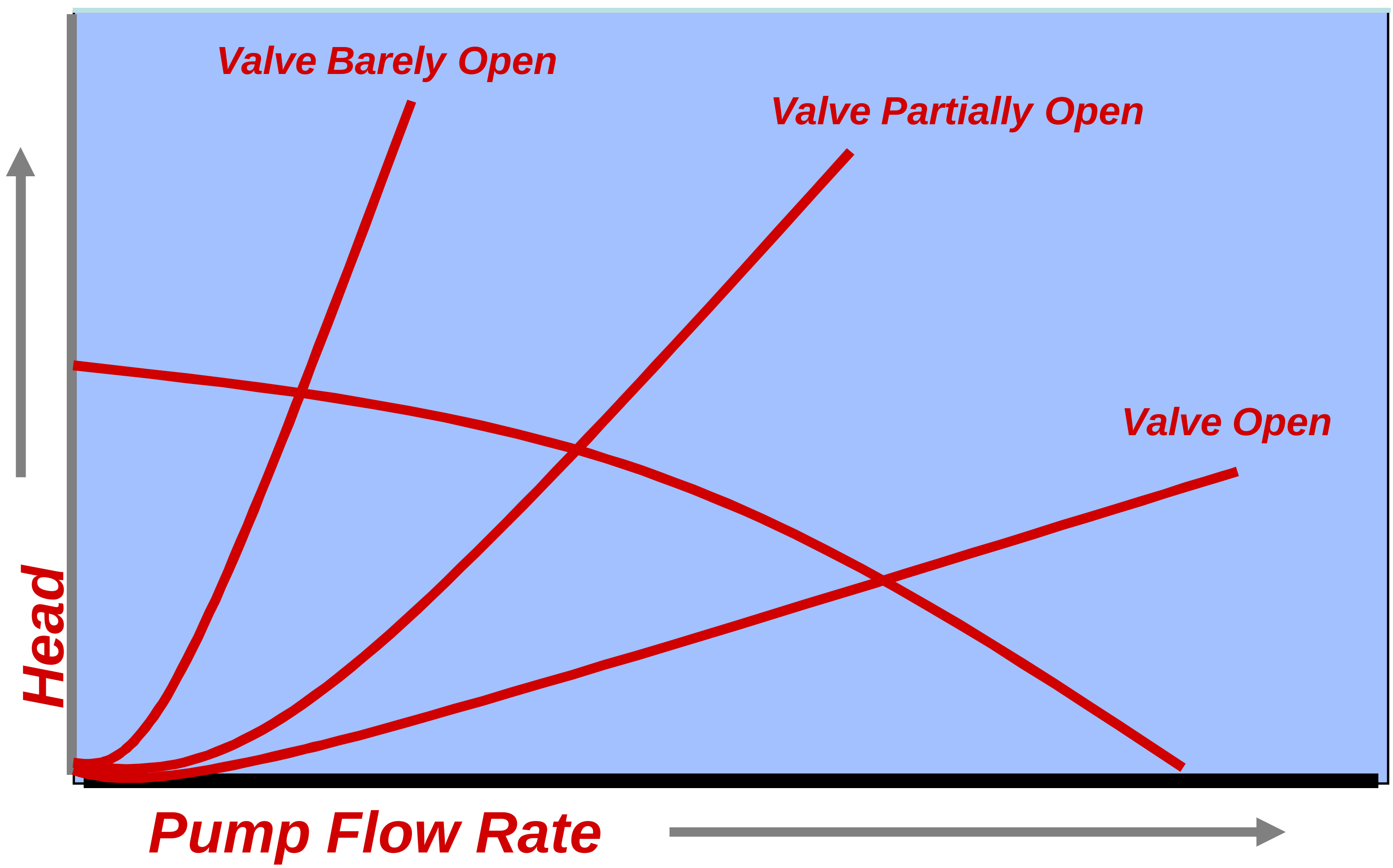
Controlling Pump Performance

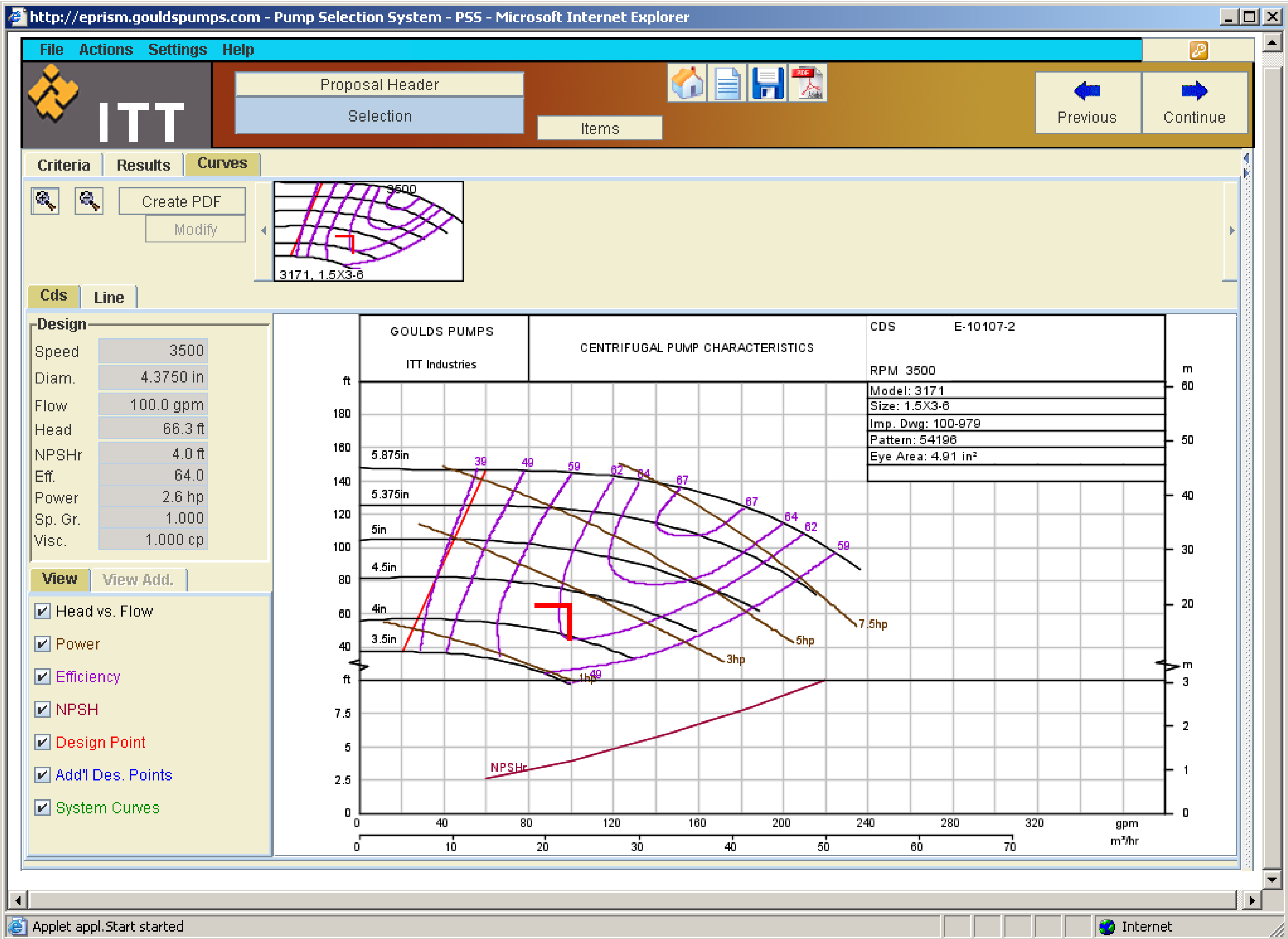


- **Changing the amount for friction loss or "Throttling the Pump" will change the pump's performance**



PUMP SELECTION




http://eprism.gouldspumps.com - Pump Selection System - PSS - Microsoft Internet Explorer
File
Actions
Settings
Help
ITT
Proposal Header
Selection
Items
Previous
Continue
Criteria
Results
Curves
Create PDF
Modify
3500
3171, 1.5X3-6
Cds
Line
Design
Speed 3500
Diam. 4.3750 in
Flow 100.0 gpm
Head 66.3 ft
NPSHr 4.0 ft
Eff. 64.0
Power 2.6 hp
Sp. Gr. 1.000
Visc. 1.000 cp
View
View Add.
Head vs. Flow
Power
Efficiency
NPSH
Design Point
Add'l Des. Points
System Curves
GOULDS PUMPS
ITT Industries
CENTRIFUGAL PUMP CHARACTERISTICS
CDS
E-10107-2
RPM 3500
Model: 3171
Size: 1.5X3-6
Imp. Dwg: 100-979
Pattern: 54196
Eye Area: 4.91 in²
5.875in
5.375in
5in
4.5in
4in
3.5in
7.5hp
5hp
3hp
1hp
NPSHr
gpm
m³/hr
Applet appl.Start started
Internet

Piping Design Equations
Heuristics for Pipe Diameter

$Liquids:$

$$D = 2.607\left(\frac{w}{\rho}\right)^{0.494}$$

$Gases:$

$$D = 1.065\left(\frac{w^{0.408}}{\rho^{0.343}}\right)$$

$D = Diameter, inches$

$w = Mass\ Flowrate, 1000\ lb/hr$

$\rho = Density, lb/\ ft^3$

Energy Loss in Piping Networks Incompressible Fluids

$$\frac{144}{\rho}\left(P_1 - P_2\right) + \frac{1}{2g}\left(v_1^2 - v_2^2\right) = \left(z_2 - z_1\right) + h_L$$

$\rho = Density,\ lb/\ ft^3$

$P = Pressure,\ lb_f\ /in^2$

$v = Velocity,\ ft/sec$

$g = Gravitational\ Acceleration,\ 32.174\ ft/\mathrm{s}^2$

$z = Elevation,\ ft$

$h_L = Head\ loss,\ ft$

$$h_L = \frac{0.00259\left(\sum K\right)Q^2}{d^4}$$

$$Q = Volumetric\ Flowrate,\ gpm$$

$$d = Pipe\ Diameter,\ in$$

$$\sum K = Sum\ of\ all\ fittings$$

$$K = f\frac{L}{D},\ straight\ pipe$$

$$K = \left(1 - \frac{d_1^2}{d_2^2}\right)^2,\ Sudden\ enlargement$$

Friction Loss Factors for Fittings

Fitting	K
Standard 90º Elbow	$30f_T$
Standard 45º Elbow	$16f_T$
Standard Tee	$20f_T$ Run $60\ f_T$ Branch
Pipe Entrance	0.78
Pipe Exit	1.0

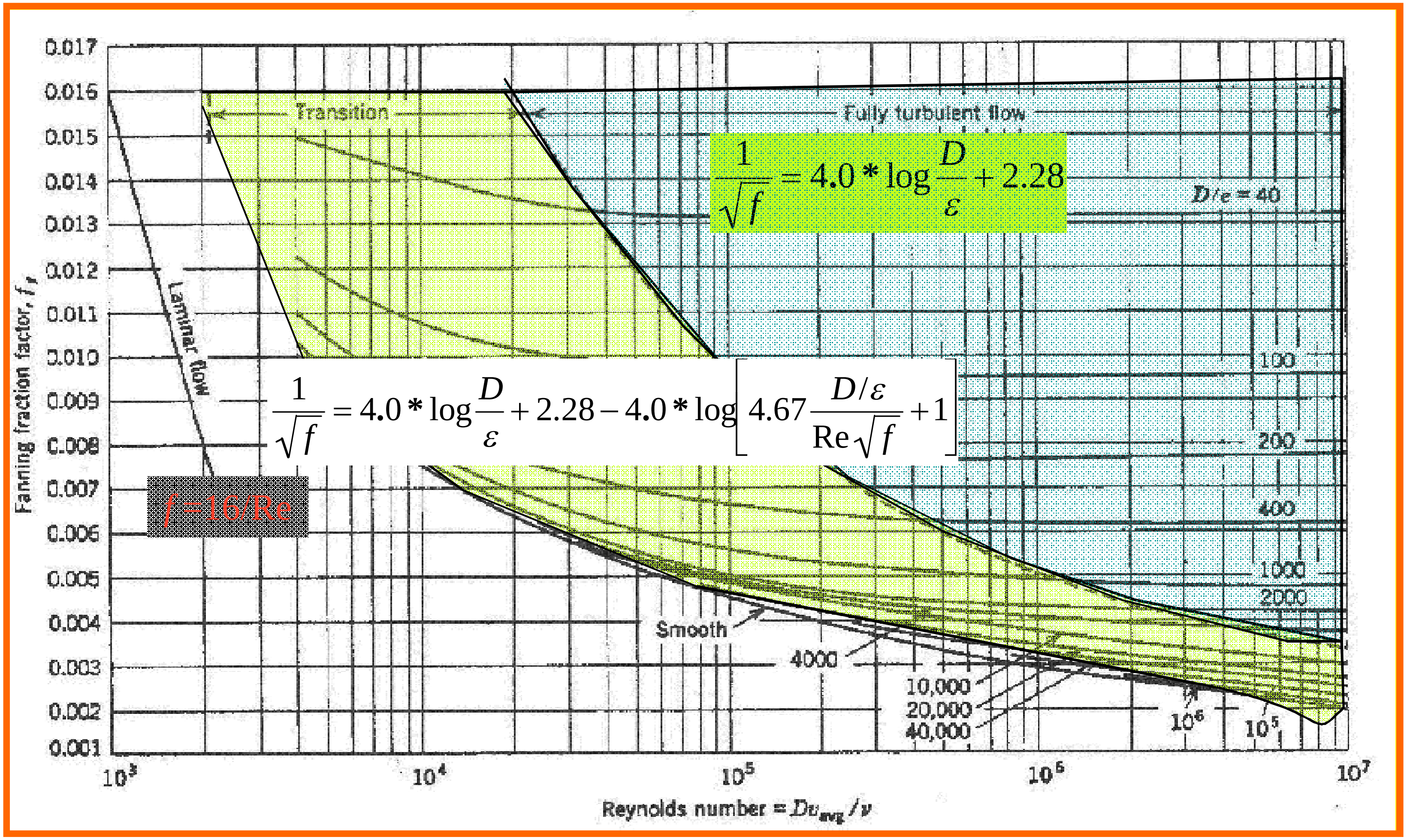
Friction Loss Factors for Valves

Valve	K
Gate valve	$8f_T$
Globe Valve	$340f_T$
Swing Check Valve	$100f_T$
Lift Check Valve	$600f_T$
Ball Valve	$3f_T$

$$\sqrt{K} = \frac{29.9d^2}{C_V^2}$$

$$C_V = Valve\ Coefficient$$

Fanning Diagram



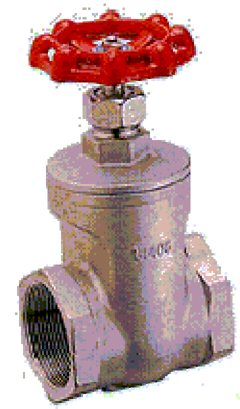
$$\frac{1}{\sqrt{f}} = 4.0 * \log\frac{D}{\varepsilon} + 2.28$$

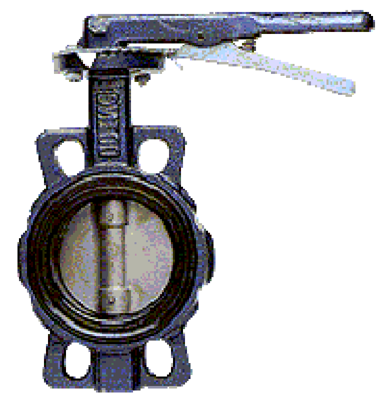
$$\frac{1}{\sqrt{f}} = 4.0 * \log\frac{D}{\varepsilon} + 2.28 - 4.0 * \log\left[4.67\frac{D/\varepsilon}{\mathrm{Re}\sqrt{f}} + 1\right]$$

$f = 16/\mathrm{Re}$

Energy Loss in Valves

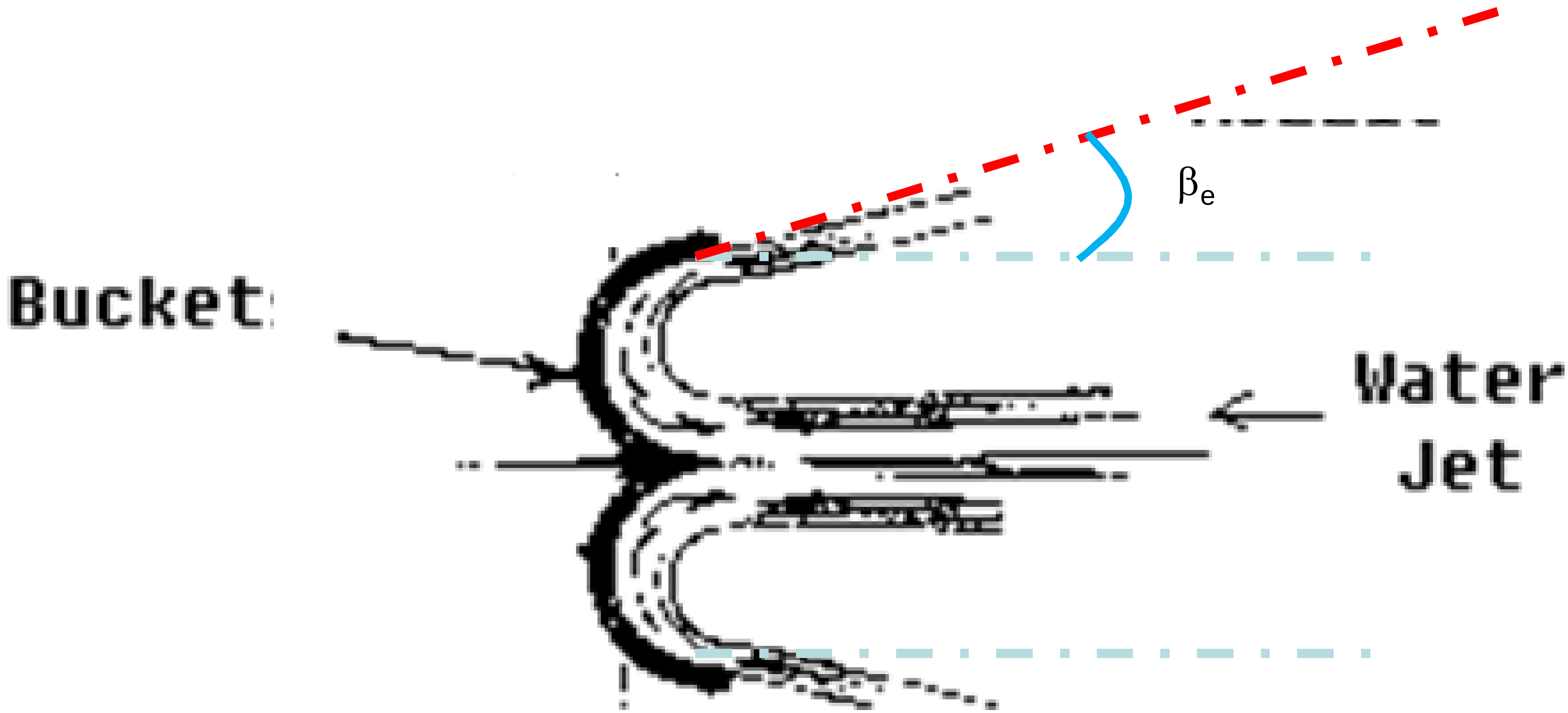
- Function of valve type and valve position
- The complex flow path through valves can result in high head loss (of course, one of the purposes of a valve is to create head loss when it is not fully open)
- E_v are the loss in terms of velocity heads





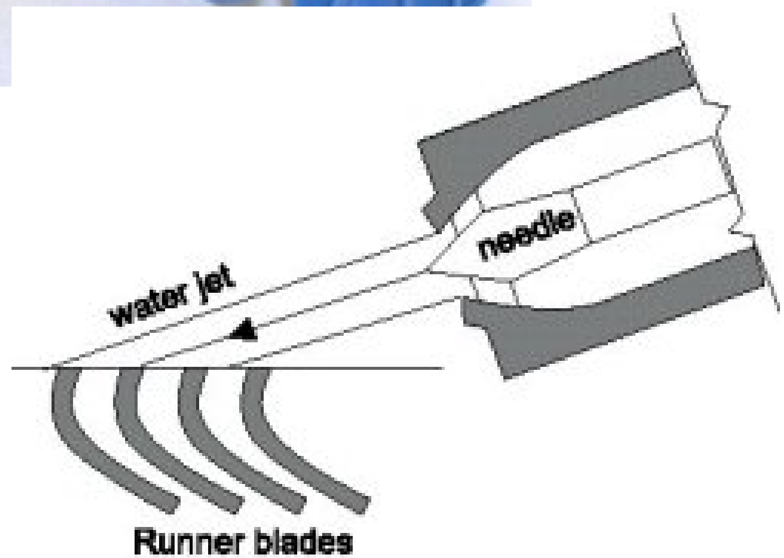
Closing Remarks on Pelton Wheel

- The first scientifically developed concept and also patented product.
- The only one option for high heads (> 600 m)
- Best suited for low flow rates with moderate heads (240m -- 600m).
- A better choice for moderate heads with medium flow rates.
- Easy to construct and develop, as it works at constant (atmospheric) pressure.
- Low rpm at moderate or marginal heads is a major disadvantage.

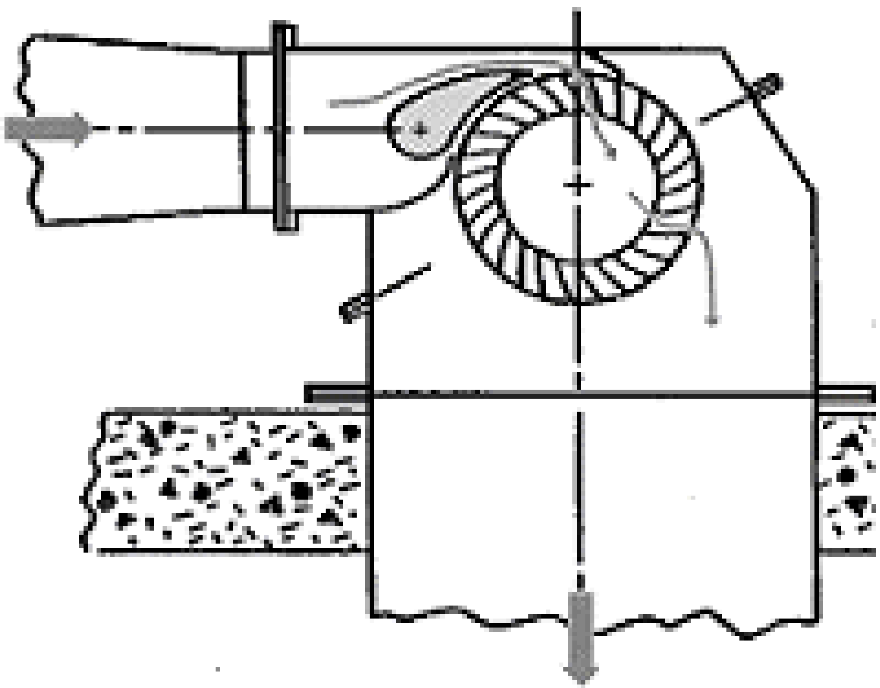


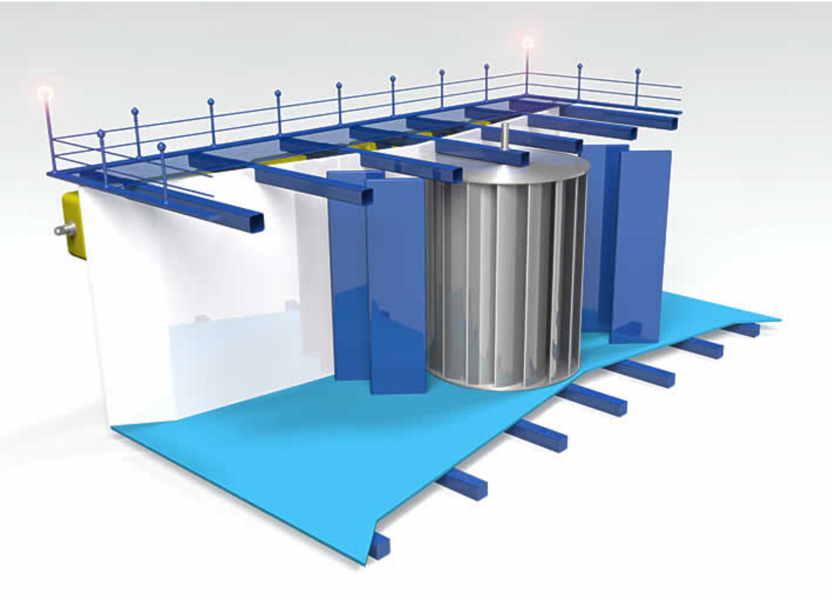
Is it possible to use Pure Momentum for Low Head Jets?

Turgo Turbine

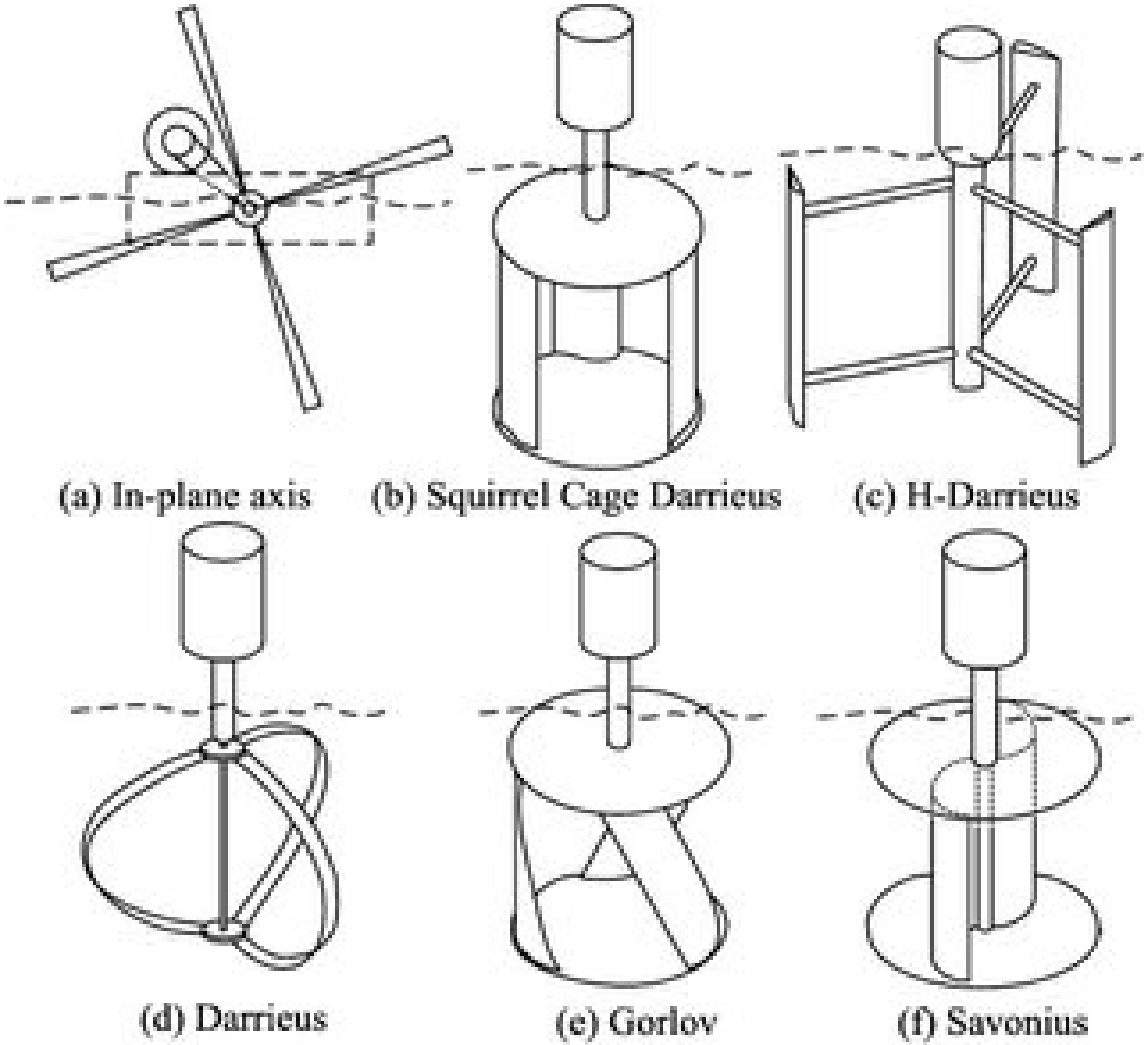


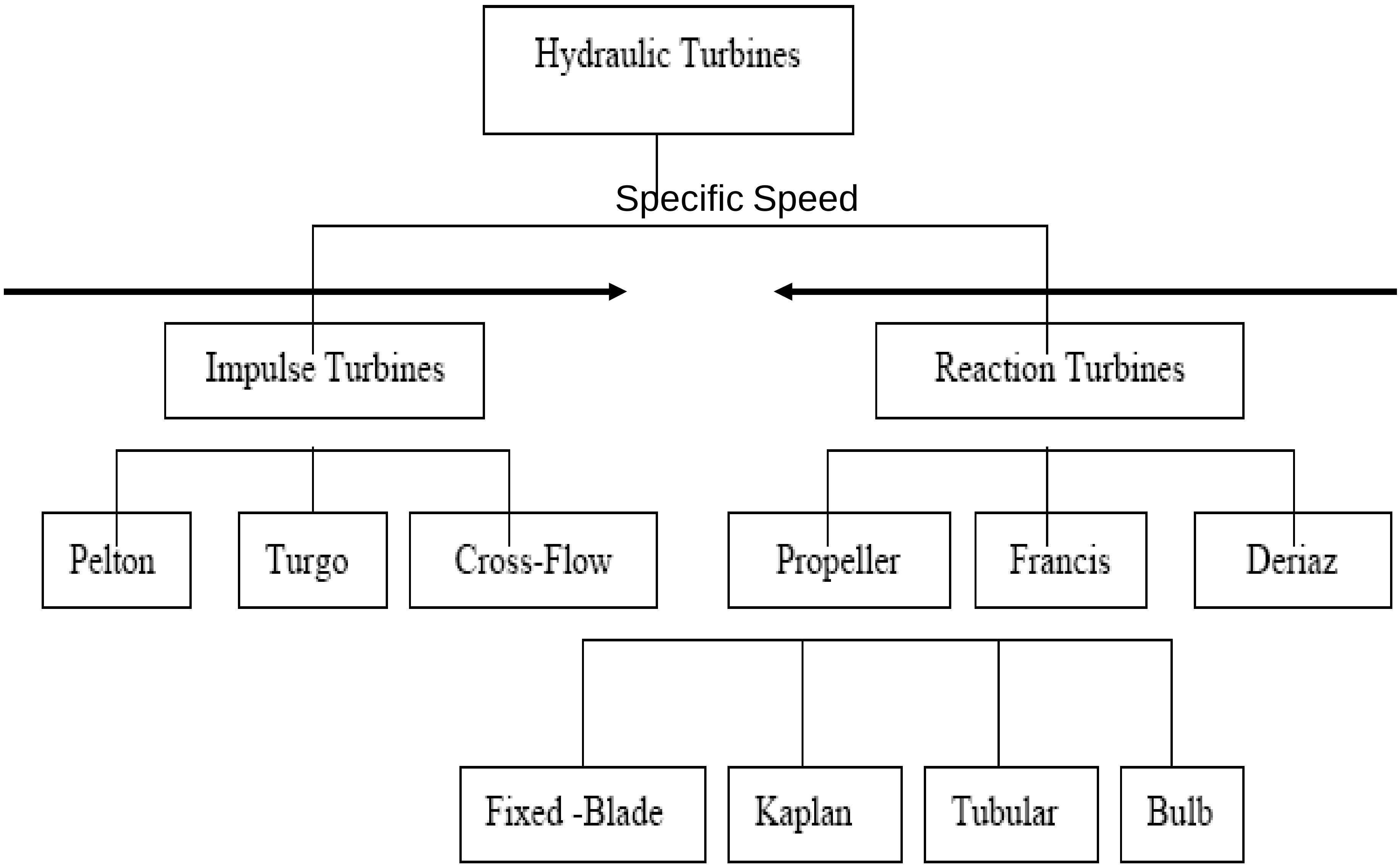
Cross-flow Turbine



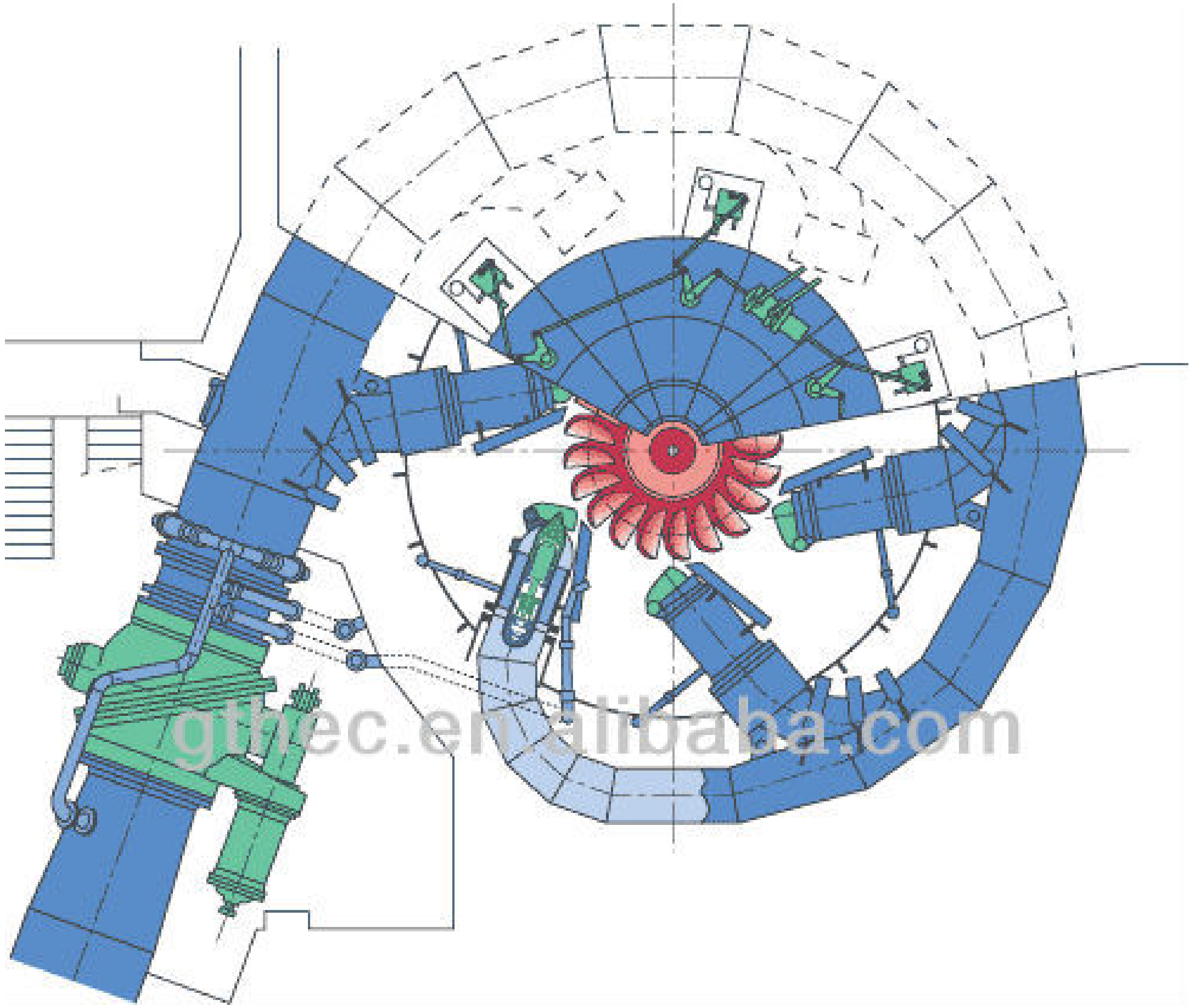


Variations of Cross-Flow Turbines

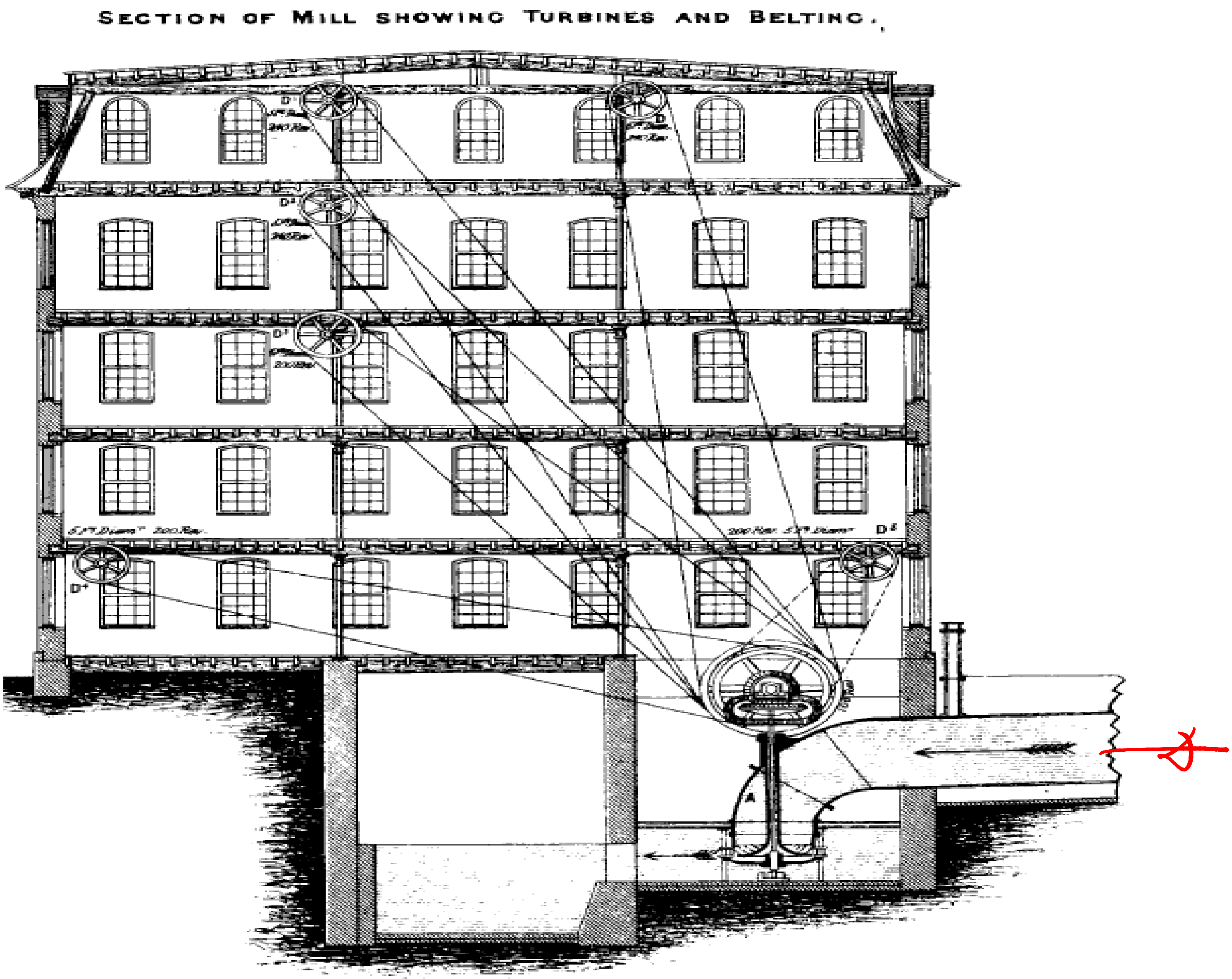



Hydraulic Turbines
Specific Speed
Impulse Turbines
Reaction Turbines
Pelton
Turgo
Cross-Flow
Propeller
Francis
Deriaz
Fixed -Blade
Kaplan
Tubular
Bulb

Only for Relative low Flow Rates



The Textile Industry : Reason for the Birth of Large Hydro-Turbines



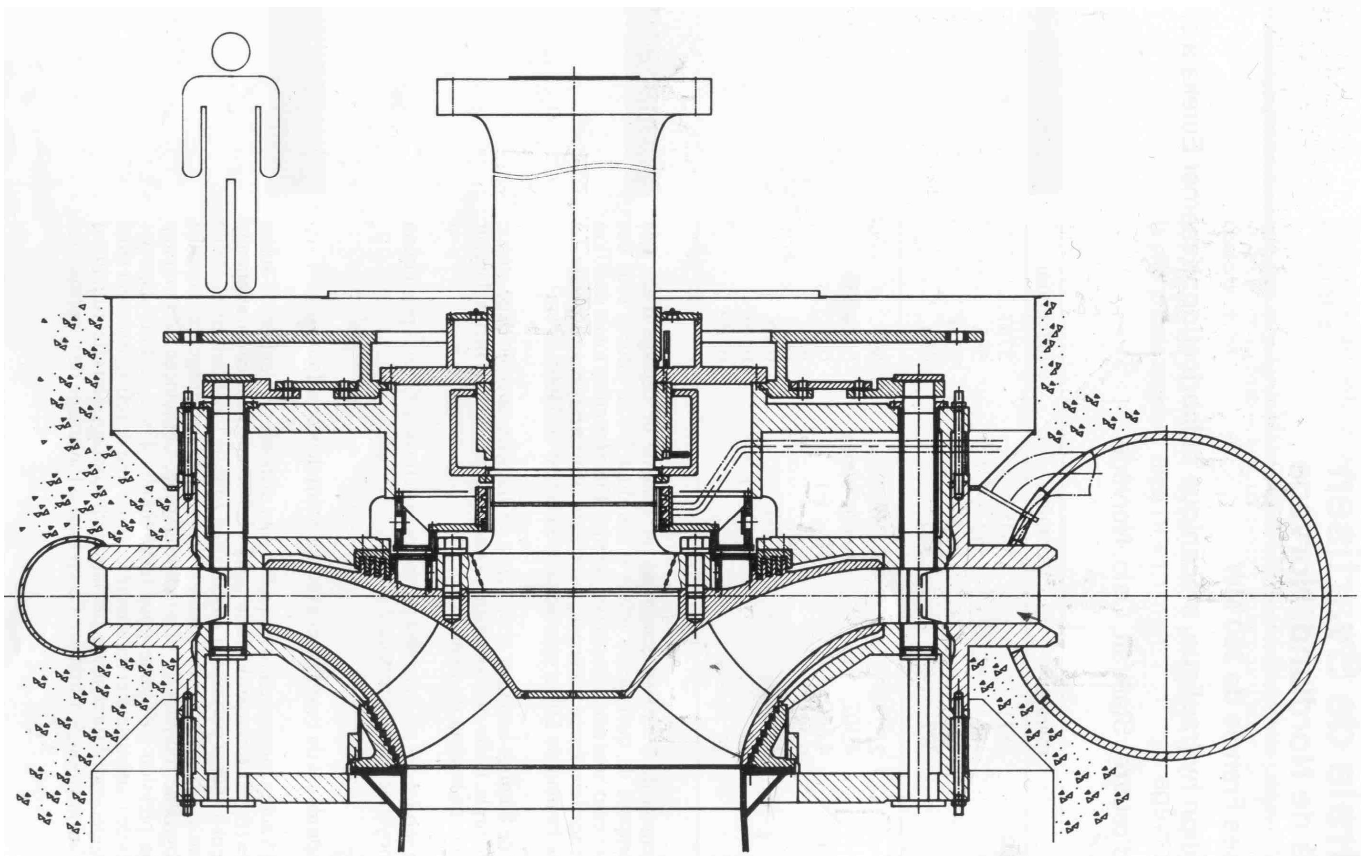
Improper Fluid Mechanics to Proper Fluid Mechanics

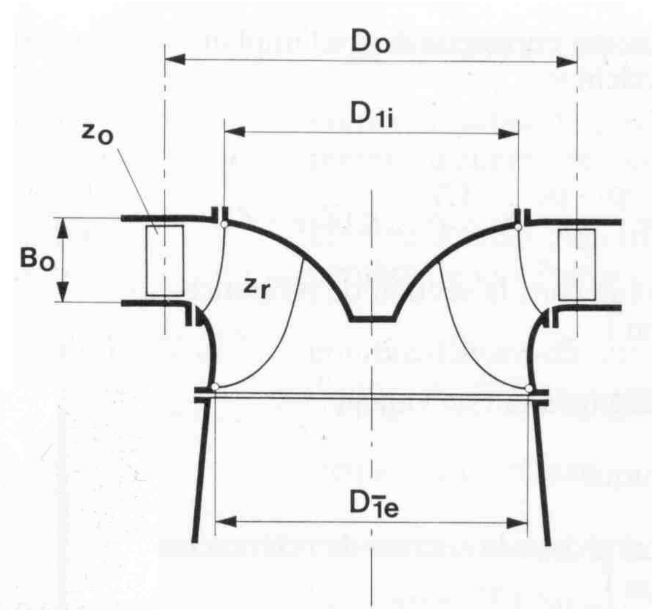
- Originally the textile mills had used waterwheels or breast-wheels that rotated when filled with water.
- These types of wheels could achieve a 65 percent efficiency.
- One such problem with these wheels was backwater which prevented the wheel from turning.

Francis turbines

- It is a reaction turbine developed by an English born American Engineer, Sir J.B. Francis.
- The water enters the turbine through the outer periphery of the runner in the radial direction and leaves the runner in the axial direction, and hence it is called 'mixed flow turbine'.
- It is a reaction turbine and therefore only a part of the available head is converted into the velocity head before water enters the runner.
- The pressure head goes on decreasing as the water flows over the runner blades.
- The static pressure at the runner exit may be less than the atmospheric pressure and as such, water fills all the passages of the runner blades.
- The change in pressure while water is gliding over the blades is called 'reaction pressure' and is partly responsible for the rotation of the runner.
- A Francis turbine is suitable for medium heads (45 to 400 m) and requires a relatively large quantity of water.

Variations of Francis : SVARTISEN





P = 350 MW

H = 543 m

Q* = 71,5 m^3/s

D_0 = 4,86 m

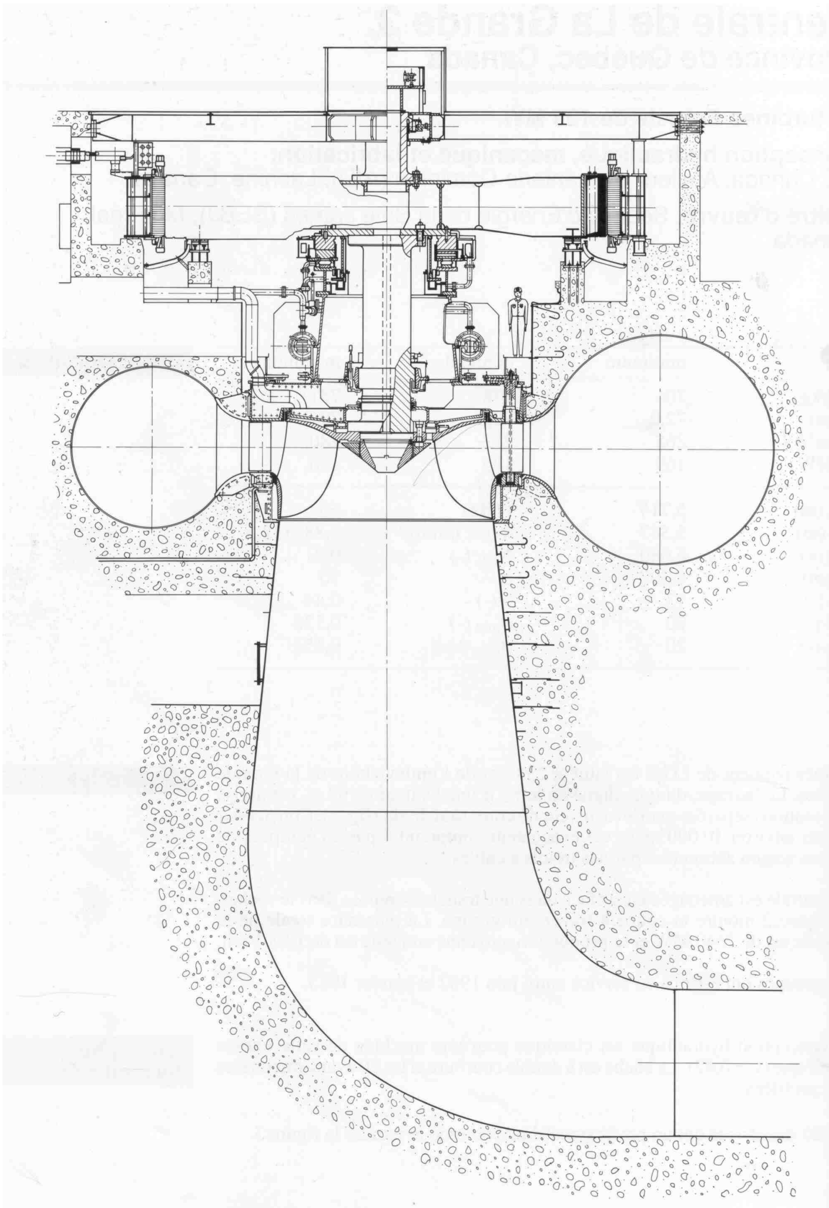
D_1 = 4,31m

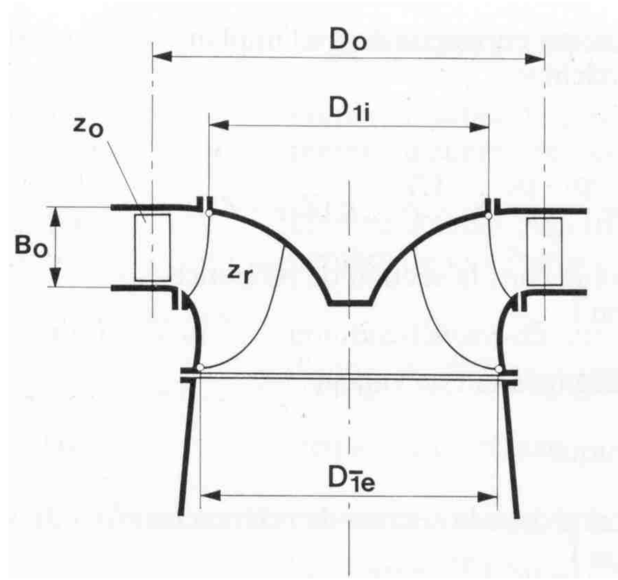
D_2 = 2,35 m

B_0 = 0,28 m

n = 333 rpm

Variations of Francis : La Grande, Canada





$P = 169$ MW

$H = 72$ m

$Q = 265\ m^3/s$

$D_0 = 6{,}68$ m

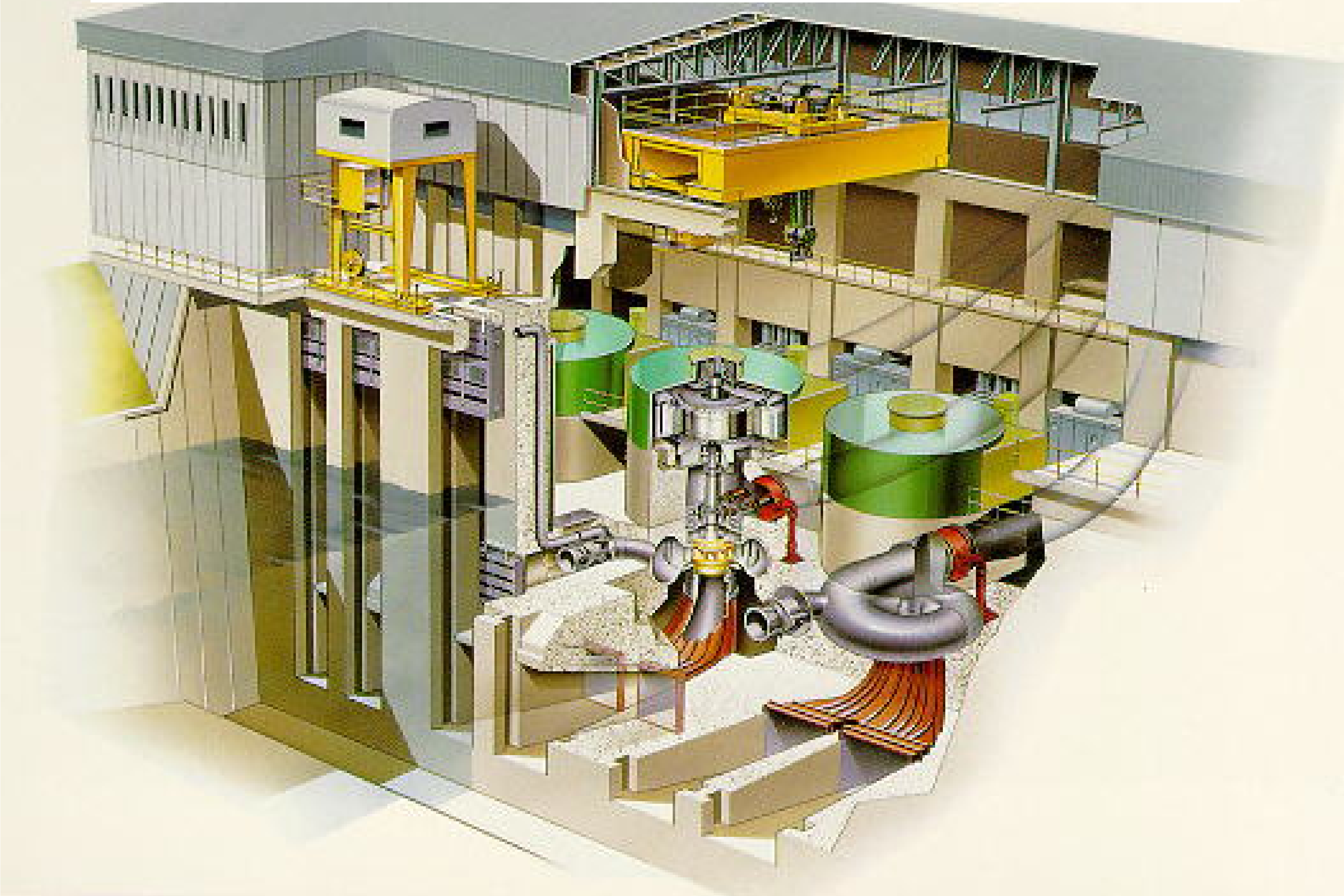
$D_{1e} = 5{,}71$m

$D_{1i} = 2{,}35$ m

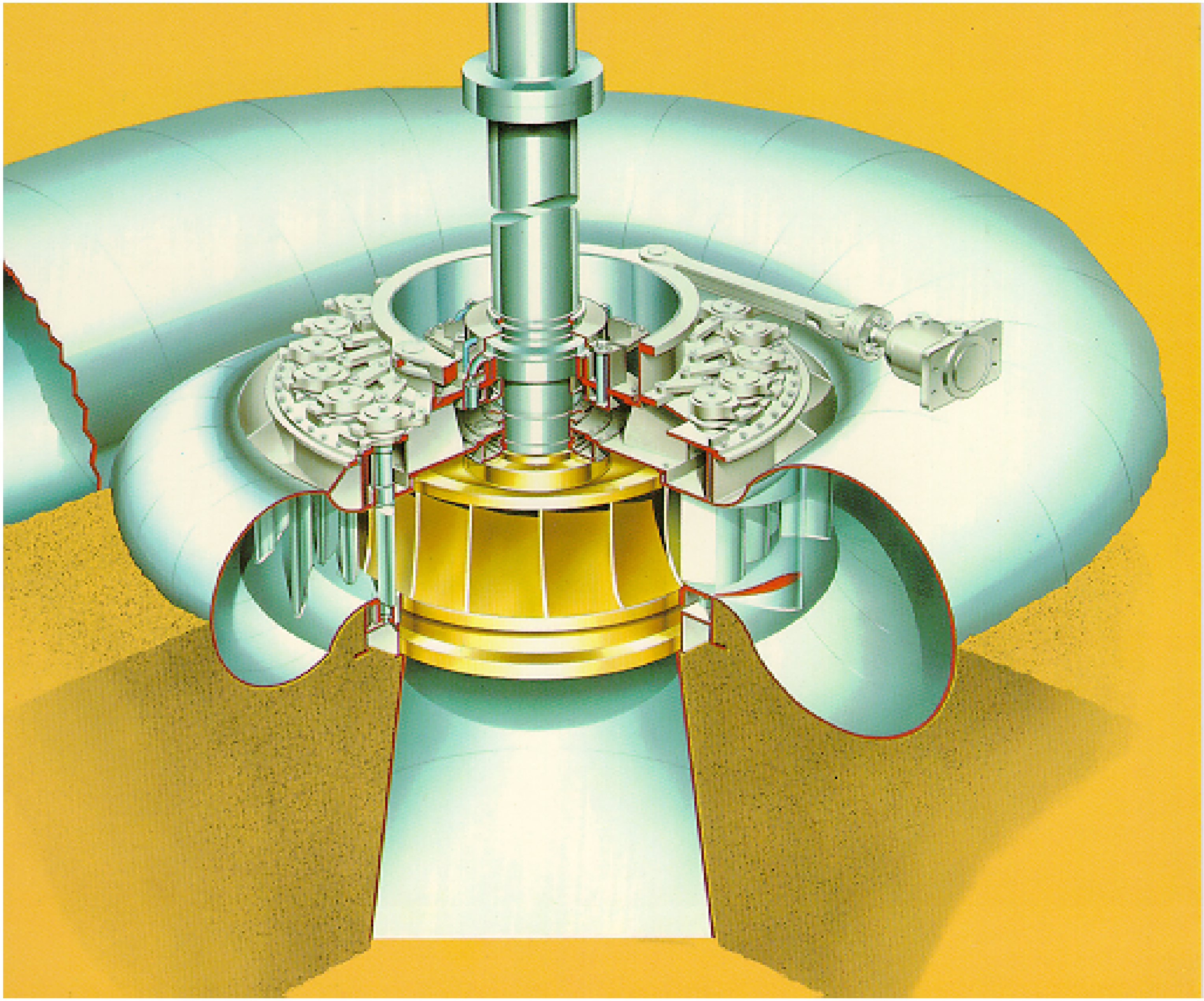
$B_0 = 1{,}4$ m

$n = 112{,}5$ rpm

The Francis Installation

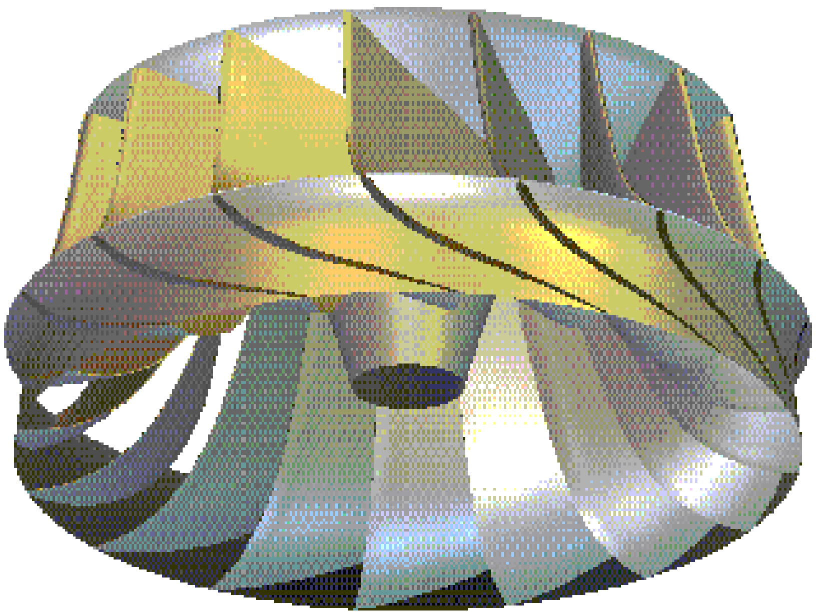


The Francis Turbine

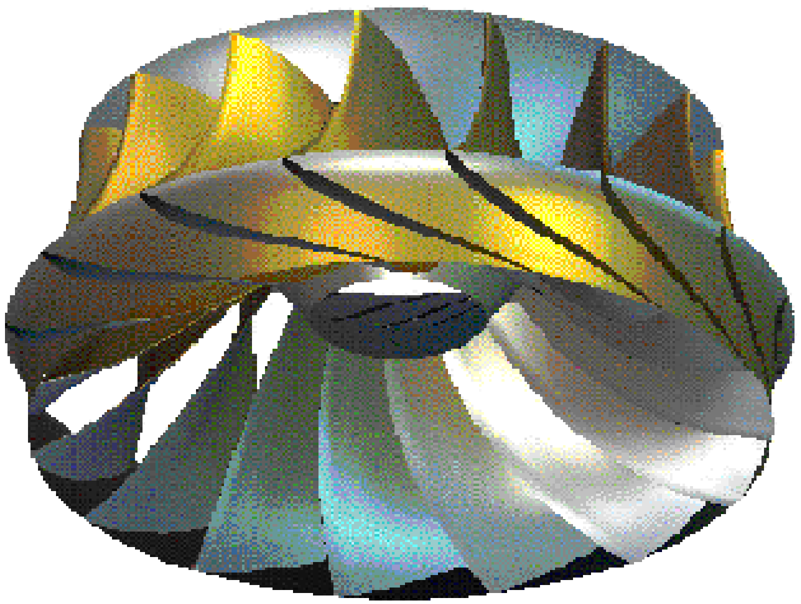


The Francis Runner

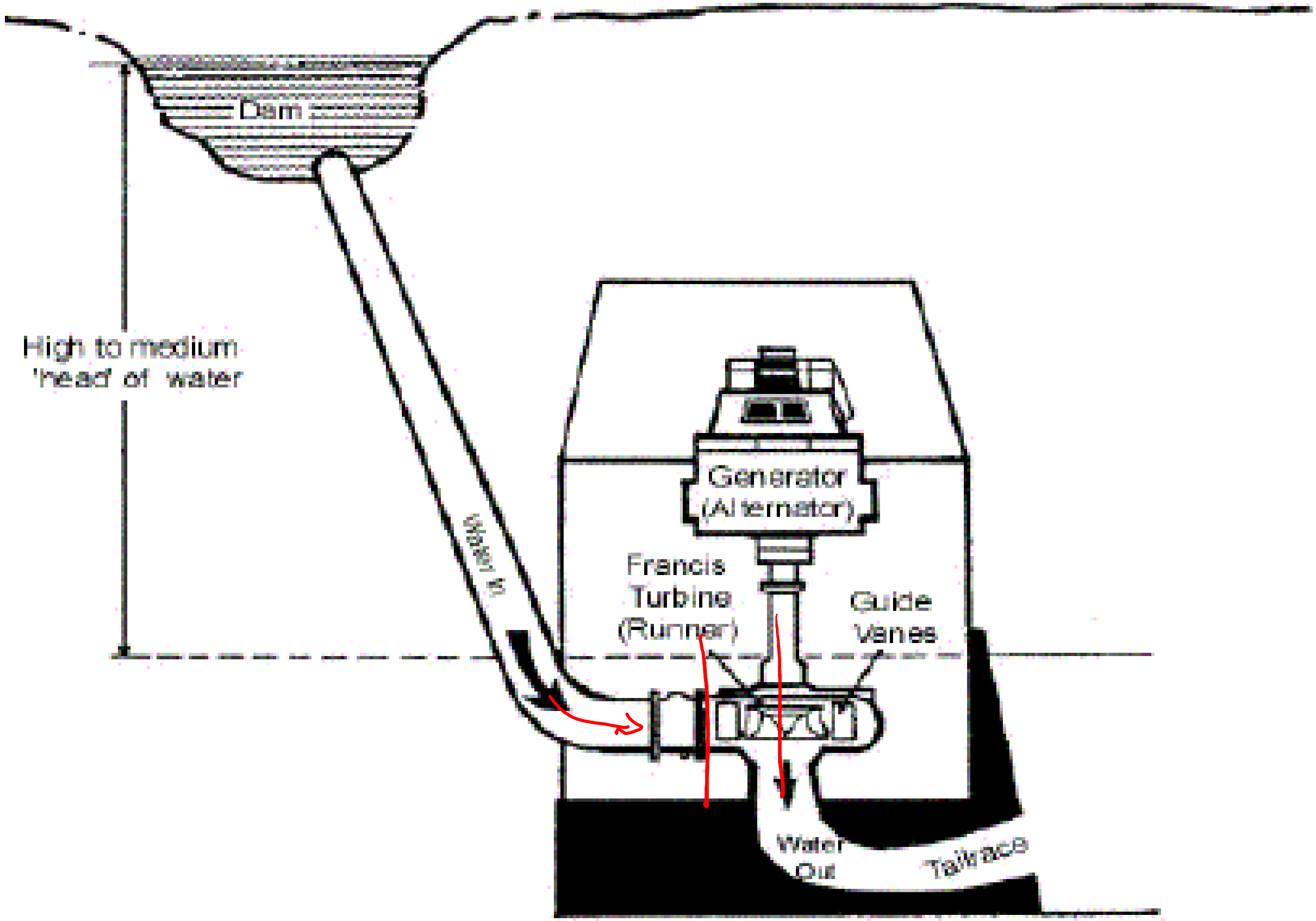
Traditional runner



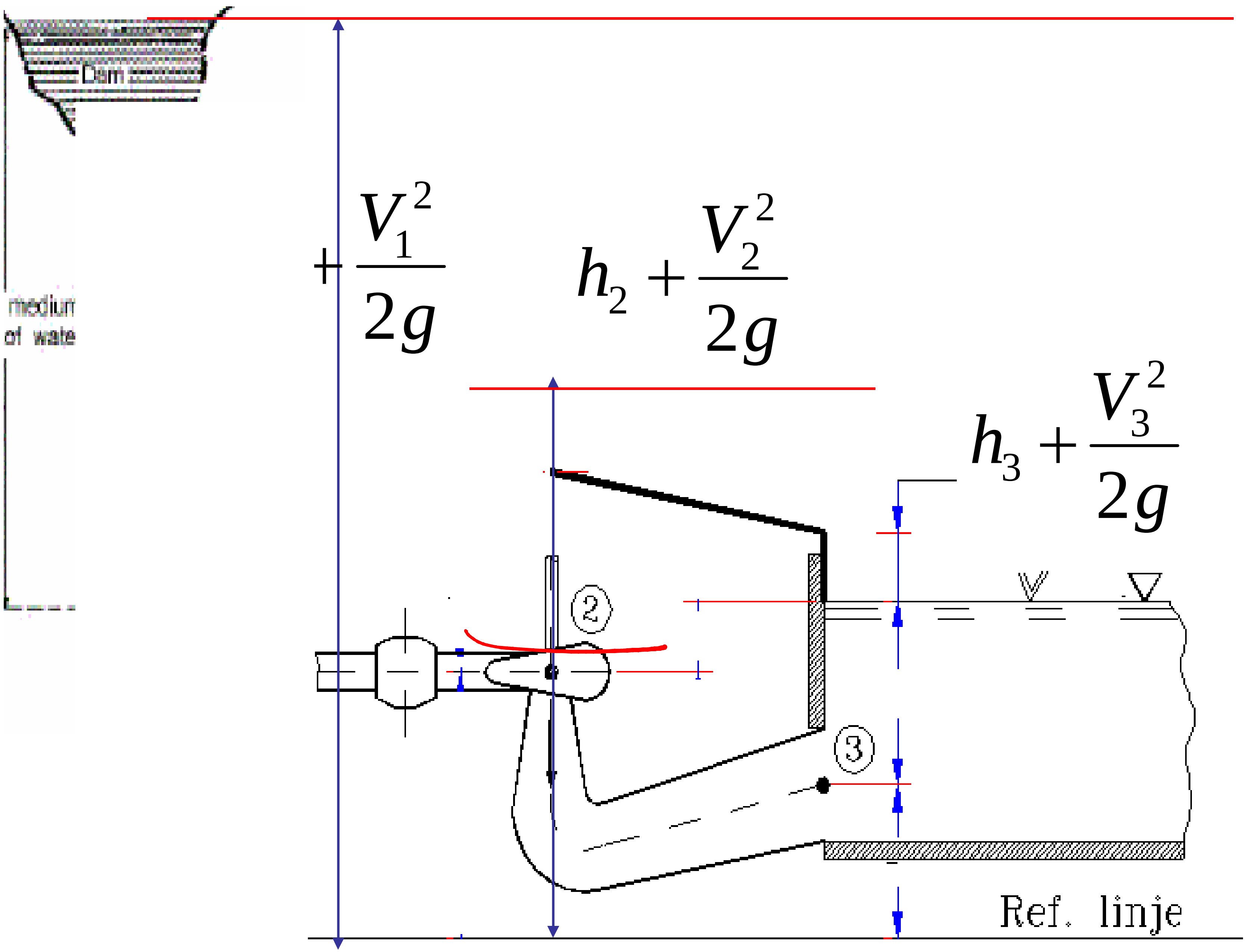
X blade runner

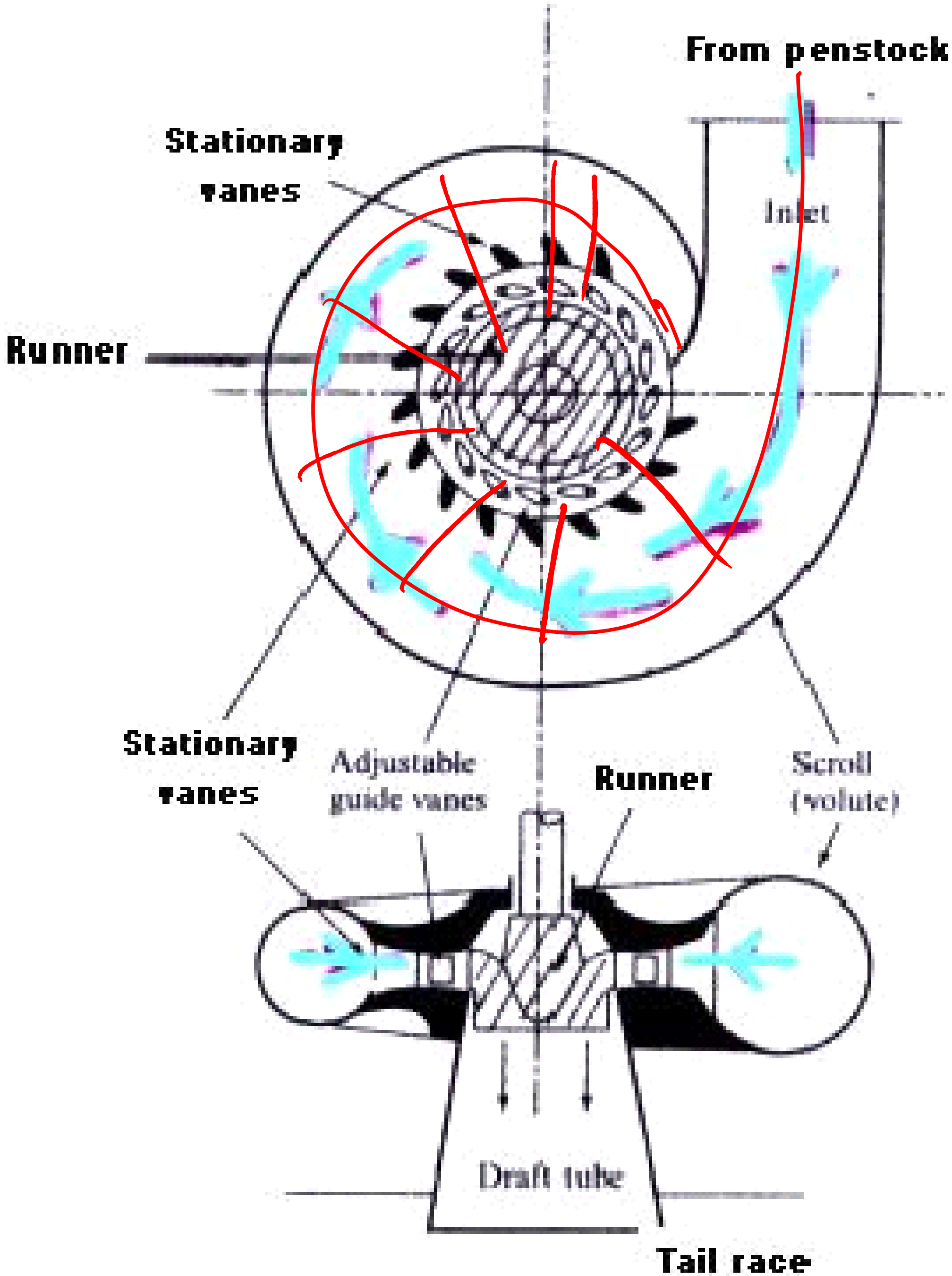


Francis Turbine Power Plant : A Continuous Hydraulic System

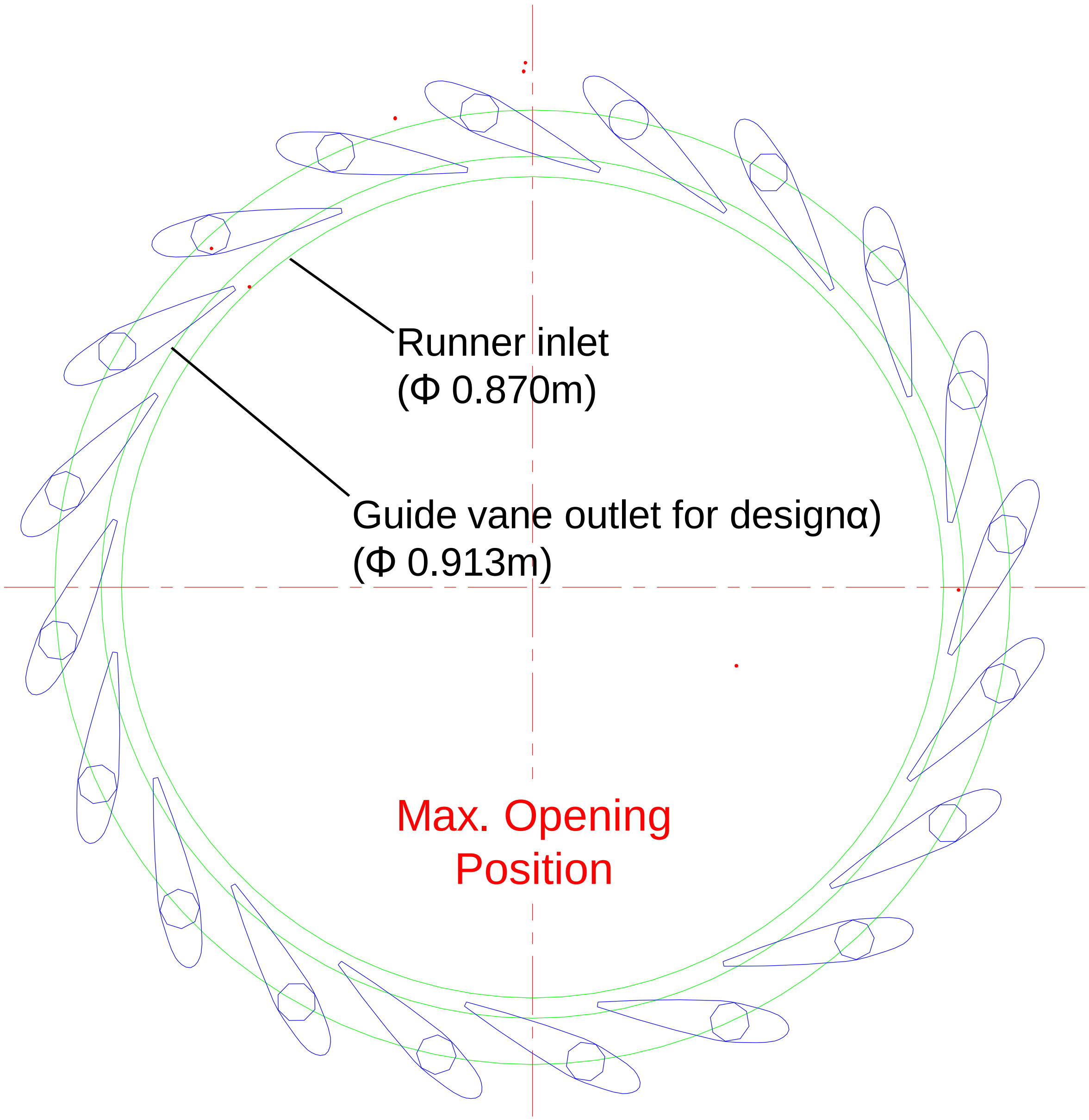


An Active Pascal Law : A Hydraulic Model for Francis Units



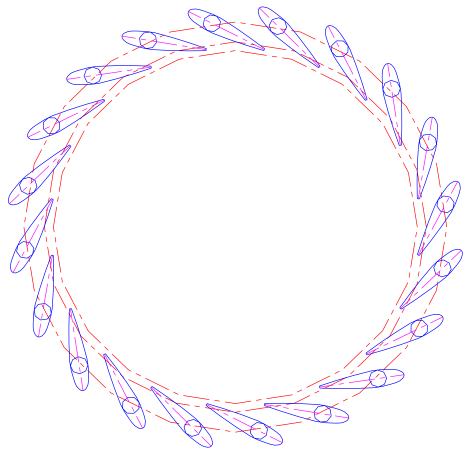


Parts of A Francis Turbine

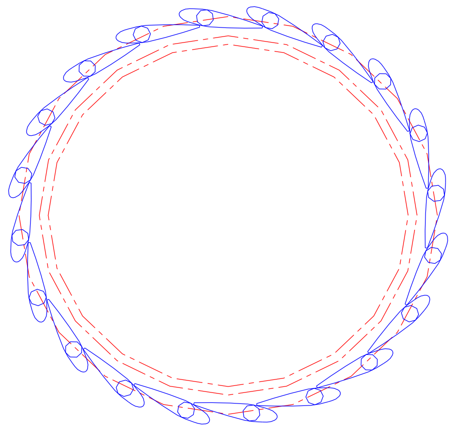

Runner inlet
(Φ 0.870m)
Guide vane outlet for designα)
(Φ 0.913m)
Max. Opening
Position

Guide vanes

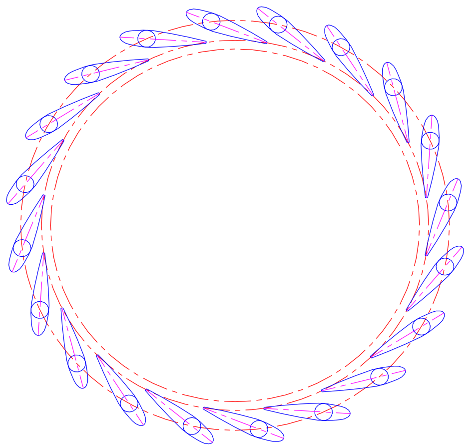
Operation of Guide Vanes



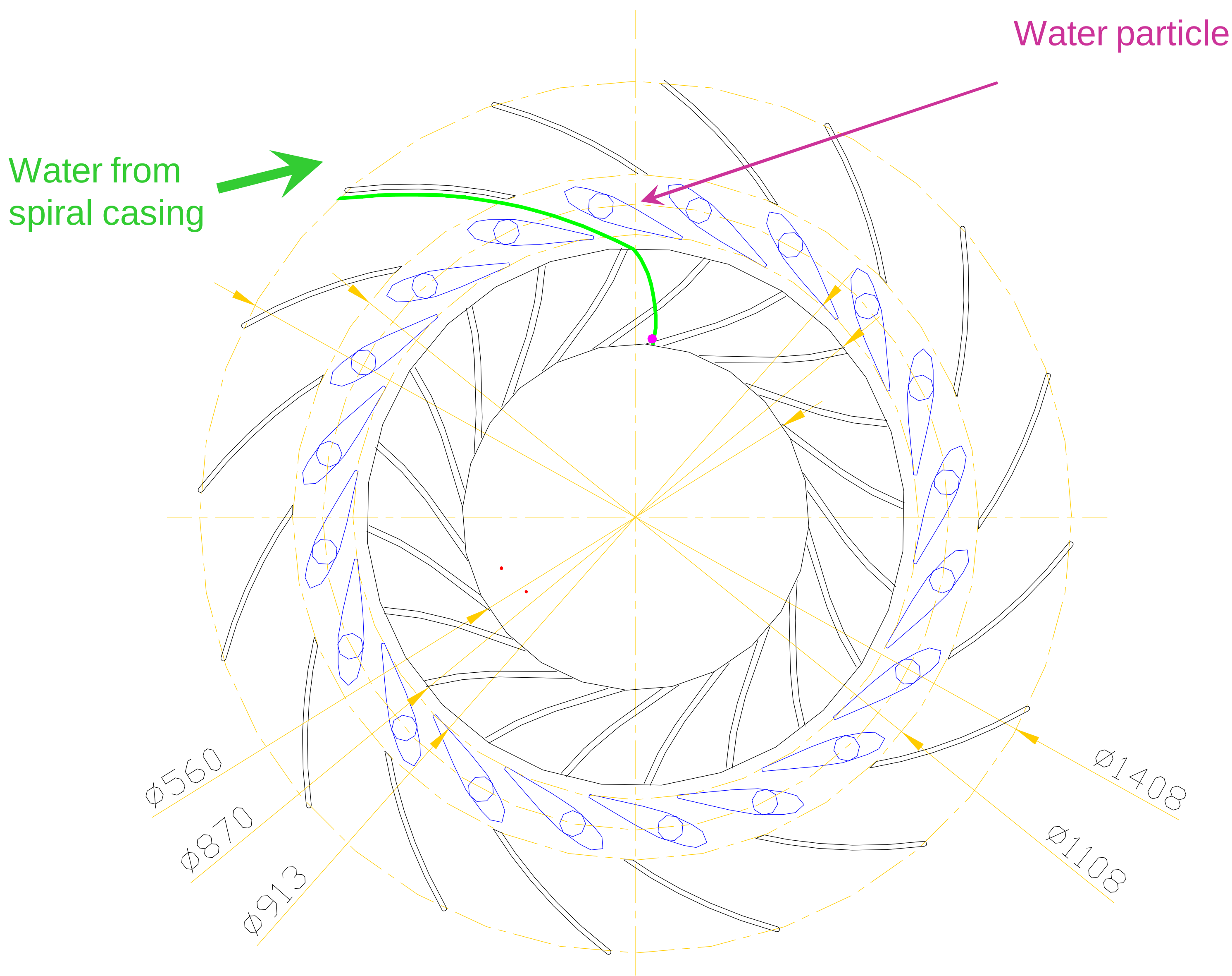
Guide vane at Design
Position α= 12.21°



Guide vane at closed position

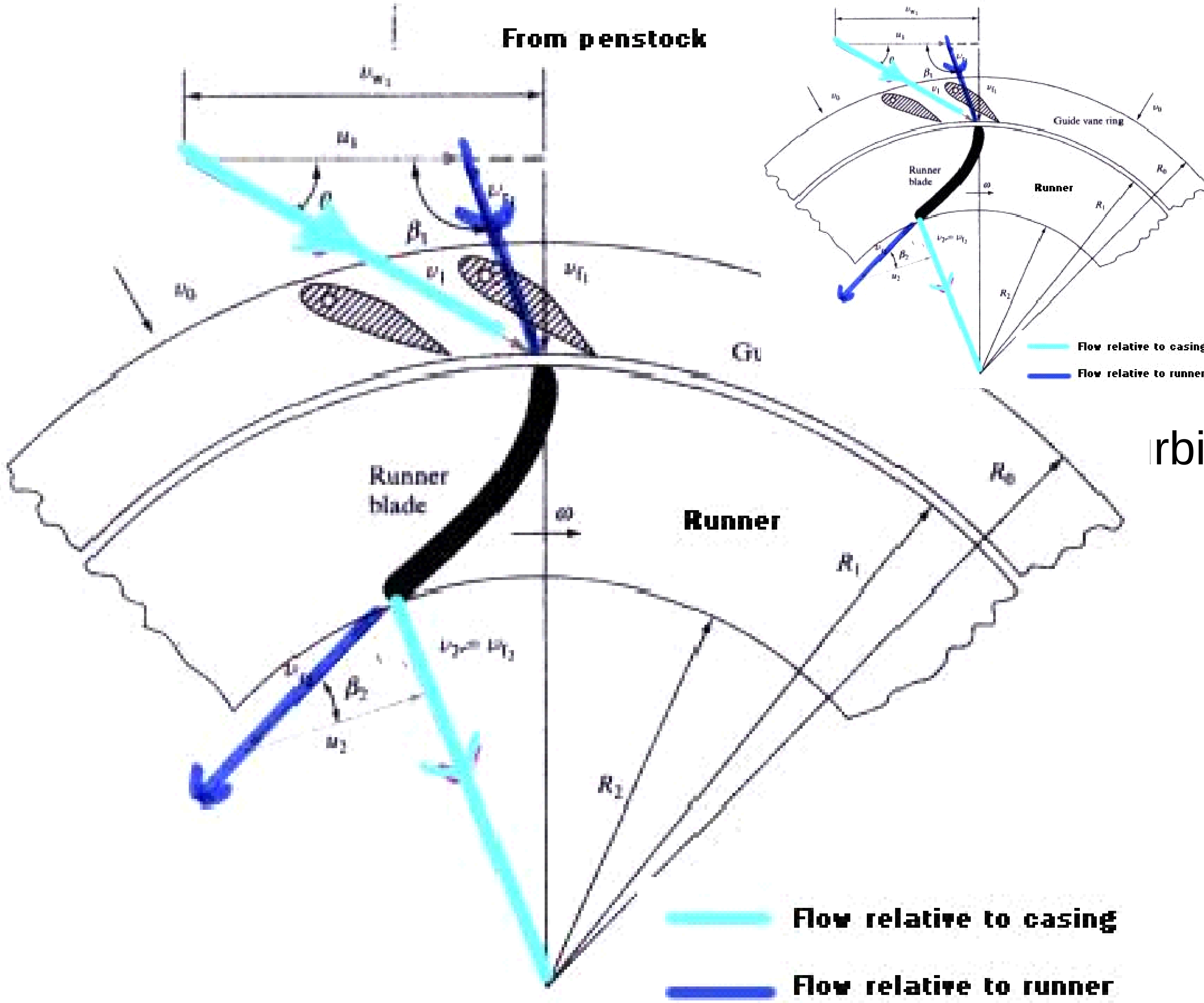


Guide vane at Max. open
Position α= 18°



Radial view
runner guide vanes and stay vanes

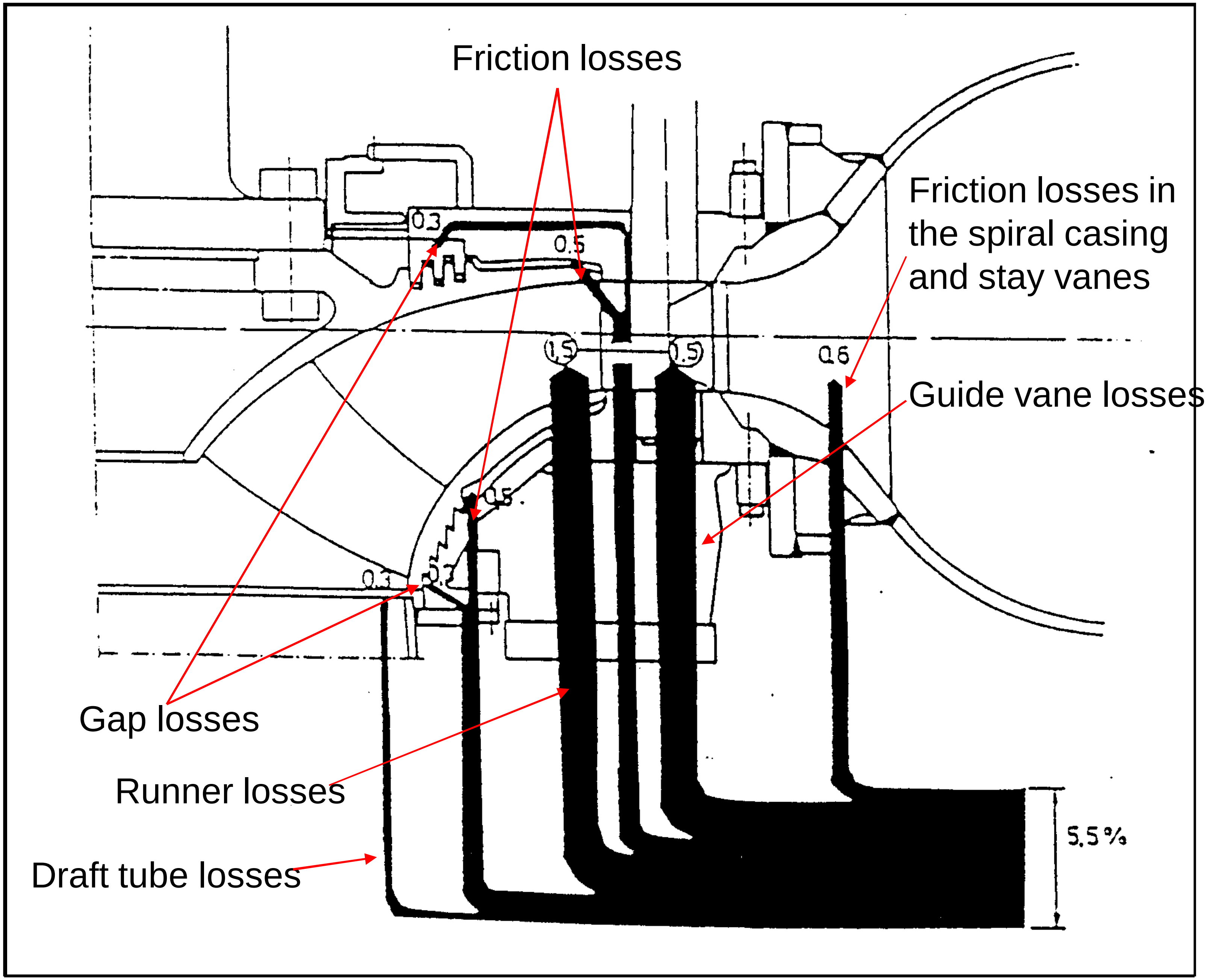
Rı


From penstock
Runner blade
Runner
Gu
Flow relative to casing
Flow relative to runner
Guide vane ring
Runner blade
Runner
Flow relative to casing
Flow relative to runner

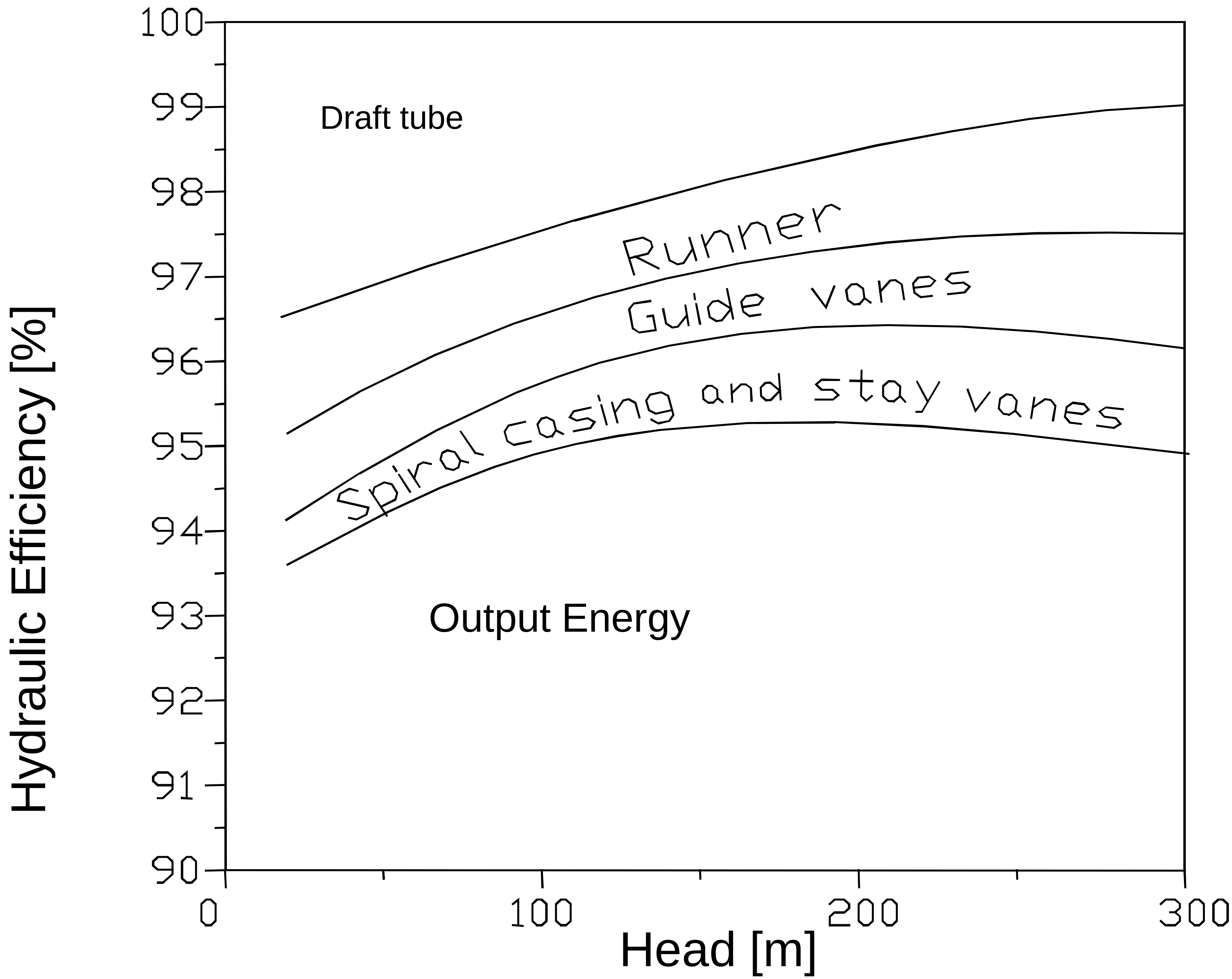
rbine

Hydraulic efficiency of Francis Hydraulic System

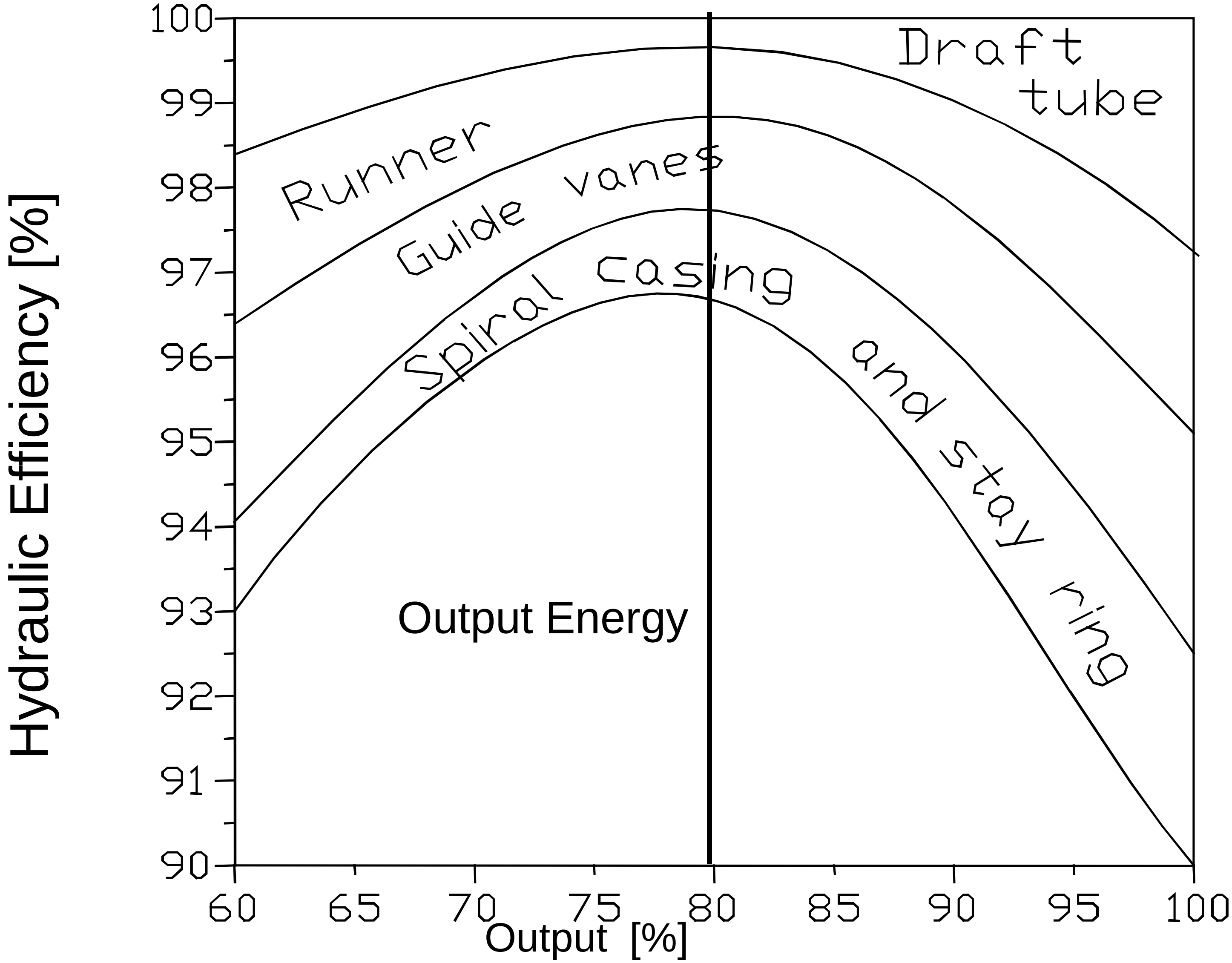
$$\eta_{hydraulic} = \frac{h_1 + \frac{V_1^2}{2g} - \left(h_3 + \frac{V_3^2}{2g} \right) - hydraulic\ Losses}{h_1 + \frac{V_1^2}{2g} - \left(h_3 + \frac{V_3^2}{2g} \right)}$$


Friction losses
Friction losses in the spiral casing and stay vanes
Guide vane losses
Gap losses
Runner losses
Draft tube losses
0.3
0.5
1.5
1.5
0.6
0.5
0.3
0.3
5.5 %

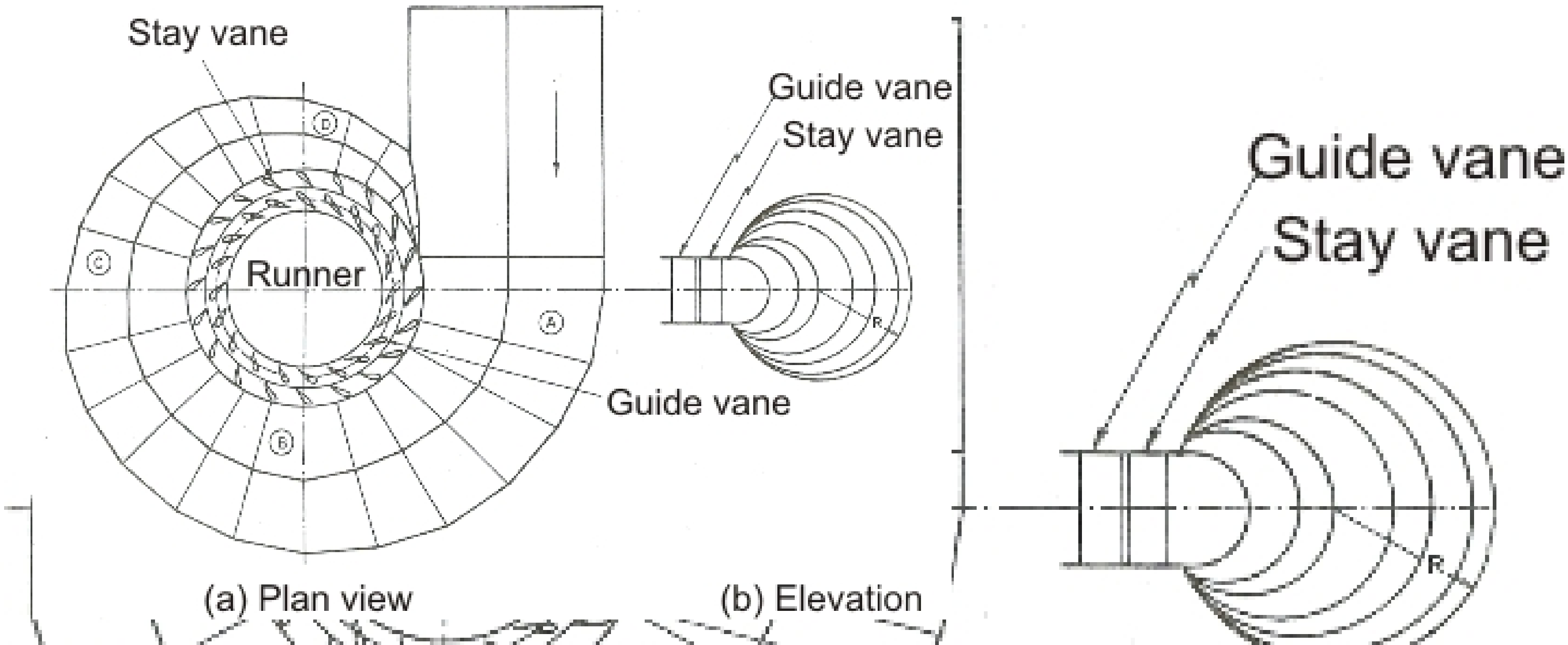
Losses in Francis Turbines



Losses in Francis Turbines



Spiral Casing



- **Spiral Casing :** The fluid enters from the penstock to a spiral casing which completely surrounds the runner.
- This casing is known as scroll casing or volute.
- The cross-sectional area of this casing decreases uniformly along the circumference to keep the fluid velocity constant in magnitude along its path towards the stay vane/guide vane.