HYDRAULIC POWER PLANTS

A TEXT BOOK FOR ENGINEERING STUDENTS

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Hydraulic Power Plants: A Textbook for Engineering Students

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FOREWORD

The purpose of hydroelectric power plant is to harness power from water flowing under pressure. As such, it incorporates a number of water driven prime movers known as water turbines.

Hydroelectric power can be developed wherever water continuously flowing under pressure is available. Dams constructed across flowing rivers divert the riverine bounty through the turbine giving rise to such useful power. However, this is not all. Water that is collected in natural or artificial lakes in the high and huge mountains, due to heavy monsoon rain, can be led down to turbines through large pipes known as penstocks.

Basic concepts of hydro power plants and fluid flow are essential in all the engineering disciplines to get better understanding of the course in professional programmers, and obviously its importance as a core subject that needs not to be overemphasized.

The author with his collaborators has been teaching the subject of hydraulic power plants for the past several years, and this monograph is essentially based on the lectures delivered by him. The lecture notes were prepared as; the author comprehend that there was no text, which could provide a coherent readily intelligible account and concise exposition of the subject.

From the experience gained through useful class discussions and feedback, the notes were revised to improve the clarity and necessary explanatory notes where added during each teaching semester. The subject matter has thus been thoroughly tested.

This book is a compilation as no claim is made of its originality. Acknowledgement is due and hereby made to all the authors whose work has been used in the preparation of this text.

Finally, this book emphasizes the need of young engineers acquiring great efficiency in using the tool of study and designing each part of hydraulic power plants such as turbines, pumps, penstocks and other parts in a simple way.

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PREFACE

Hydraulic machines-hydraulic turbine, pumps (water and oil types) and reversible hydraulic machines (pump-turbine) are applied in hydroelectric power plants, and water supply system as well as in thermal nuclear and pumped-storage station. In addition, pumps are widely used in the construction of hydraulic structures, such as dams, canals, river and sea ports.

The book describes the construction of hydraulic power plants and treats the theory of the working process for each part, *i.e.* the kinematic and dynamic of the liquid flowing through hydraulic machine and systems, only in the scope necessary for understanding their operation conditions and basic calculation relationships.

The book contains a large number of drawings and charts. It also includes the most important specification and working examples and solved problems, which can be applied in designing and maintenance of hydroelectric power plants, pumping stations and pump installation.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

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CHAPTER 1

The Momentum Equation and Its Application

Abstract: The major encountered in the hydraulic machine is to find the power developed (or consumed) by (or in) a particular machine. A turbine produces power while pumps, compressors, and fans consume power to run. The power is determined from the dynamic force or forces which are being exerted by the flowing fluid on the boundaries of the flow passage and which are due to the change of momentum. These are determined by applying "Newton's second law of motion".

In this chapter, we present the momentum equation and fluid dynamics forces in a simple way and a step by step manner related to the types of prime movers, turbines, pumps, water wheels ….*etc*. The force and power calculations using the velocity diagram for each type are presented too.

The derivation of Bernoulli's equation for relative motion based on consideration of momentum is very useful to present fluid motion inside a turbine runner or pump impeller of a centrifugal pump, which is shown in this chapter with solved problems.

Keywords: Bernoulli's equation, Momentum equation, Velocity diagram.

1.1. MOMENTUM AND FLUID DYNAMIC FORCE

Network's second law for a system Eq. (1.1) is used as a basis for determining the control volume form of the linear momentum equation. The linear momentum of a system is the product of its mass and velocity. Let **m** be the mass of fluid with velocity **V** as follows:

$$\sum F = \frac{d(m\mathrm{v})}{dt} \quad \textbf{(1.1)}$$

According to that, the general equation across a control volume becomes

$$\frac{\partial}{\partial t}\int_{\mathrm{cv}} \rho \mathrm{v} dV + \int_{\mathrm{cs}} \mathrm{v}\rho \mathrm{v} dA \quad \textbf{(1.2)}$$

Where cv: control volume

cs: control surface

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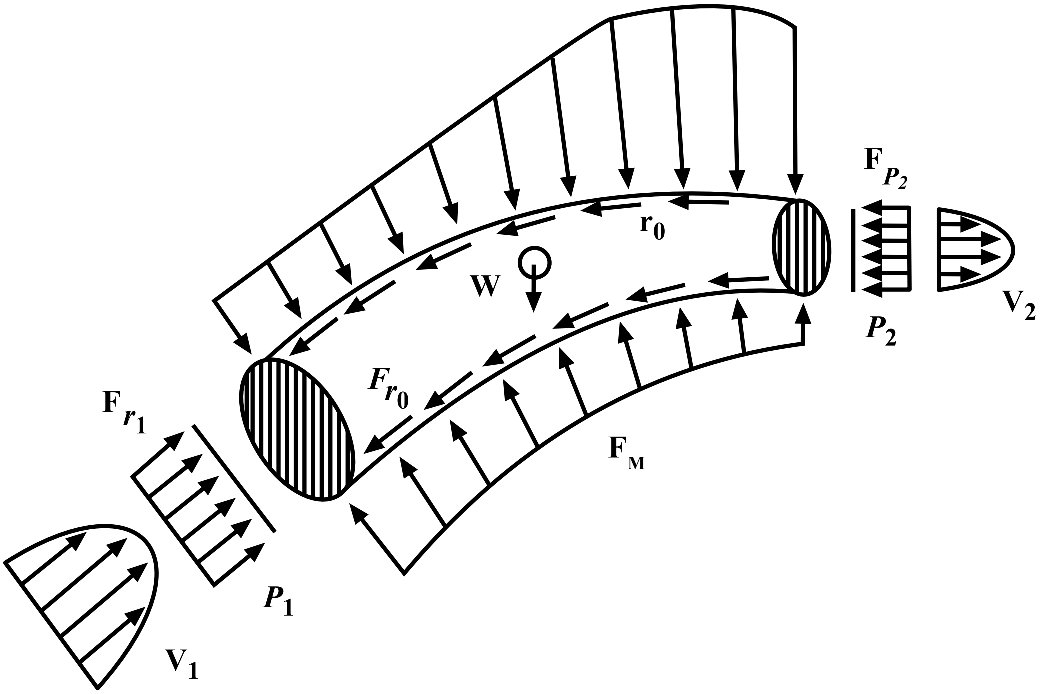

Fig. (1.1). Control volume for flow through a pipe.

The flow is assumed to be steady and the resultant forces and flow parameters are established on the control volume and consist of both resultant forces and equivalent momentum exchanges at the inlet and the outlet (**Fig.1.1**). Therefore, the vector sum of the real applied external force is defined as follows [1]:

$$\sum F = W + F_{p_1} + F_{p_2} + F_{\tau_0} + F_N \quad \textbf{(1.3)}$$

$W -$ Is the weight force. The control volume fluid has a weight acting in the direction of gravity.

$F_{p_1}.F_{p_2} -$ The fluid pressure at inlet and outlet creates a pressure force on each face$=$ PA.

$F_{\tau_o} + F_N -$ The shear stress and the normal stress at the wall or control surface is primarily responsible for maintaining the geometry of the flow field. The stresses are exceedingly difficult to separate therefore, they are lumped together at this point into a **resultant or reaction force** vector **F**, which will act at the center of gravity of the control volume.

The direction and intensity of **F** typically depend on the application. *i.e.*

For Pumps

F- The force exerted by the boundary on the fluid (resultant force) *i.e*. positive.

For Turbine

F- The force exerted by the fluid on the boundary (reaction force (R)) *i.e*. negative

The momentum exchange M_1 and M_2 at the inlet and outlet, respectively, must be analyzed. For steady flow, the right–hand portion of Eq. (1.2) is written as:

$$M_1 + M_2 = -(\rho\overrightarrow{\mathrm{v}_1}A_1)\overrightarrow{\mathrm{v}_1} + (\rho\overrightarrow{\mathrm{v}_2}A_1)\overrightarrow{\mathrm{v}_2} \qquad \textbf{(1.4)}$$

Or

$$M_1 + M_2 = -\rho Q\overrightarrow{\mathrm{v}_1} + \rho Q\overrightarrow{\mathrm{v}_2}(A_1)\overrightarrow{\mathrm{v}_2} \qquad \textbf{(1.5)}$$

When the velocity at the control surface is perpendicular to the area and the velocity is uniform across the respective area.

The minus sign indicates that the momentum is entering the control volume.

The final form at the steady control volume form of "Newton's second law" is

$$W + F_{p_1} + F_{p_2} + F = M_1 + M_2$$

Or

$$\sum F = M_1 + M_2 \qquad \textbf{(1.6)}$$

$$\sum F = \dot{m}\left(\vec{V}_{out} - \vec{V}_{in}\right) \qquad \textbf{(1.7)}$$

This equation is important in the study of turbomachine as it enables to determine the force developed by a fluid machine.

CHAPTER 2

Impulse Water Turbine

Abstract: Impulse water turbine (Pelton turbine or Pelton wheel) is the standard type of turbines that are widely used nowadays. It is also called a free jet turbine. Pelton turbine operates under the high head of water and therefore, requires a comparatively less quantity of water.

In this chapter, the components of hydro-electric power plants using this type of turbine are presented with neat sketches. Theory of power, all mathematical calculations using velocity diagrams, solutions for single or multi-sets, power regulation components, supply, and discharge systems are also presented. Finally, solved problems are illustrated in detail at the end of this chapter.

Keywords: Components of impulse turbine, Pelton turbine, Power regulation mechanisms, Supply and discharge system.

2.1. COMPONENTS OF THE PELTON TURBINE

The impulse turbine runs by the impulsive water force (Pelton wheel). It is typically used for high-water head applications within a range of 300 to 1500 m, 0.5 to 20 m^3/s, and 200 MW for water head, flow rate, and net output power, respectively. The main components of the impulse turbine are shown in Fig. (**2.1**) [2].

1- Guide Mechanism: the primary function of the guide mechanism is to control the quantity of water that is passing through the nozzle and striking the buckets. It consists of the nozzle and the governor.

2- Buckets and Runner: each bucket is divided vertically into two parts by a splitter, which is a sharp edge in the center, giving the shape of a double hemispherical cap.

3- Casting: the casting of the Pelton wheel has no hydraulic function to perform. It is necessary only to prevent water from splashing, guide the water to the tailrace, and also works as a safeguard against accidents.

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4- Hydraulic Brake: this part consists of a small nozzle fitted in such a way that on being opened, it directs a jet on the back of the buckets to bring the revolving runner quickly to rest.

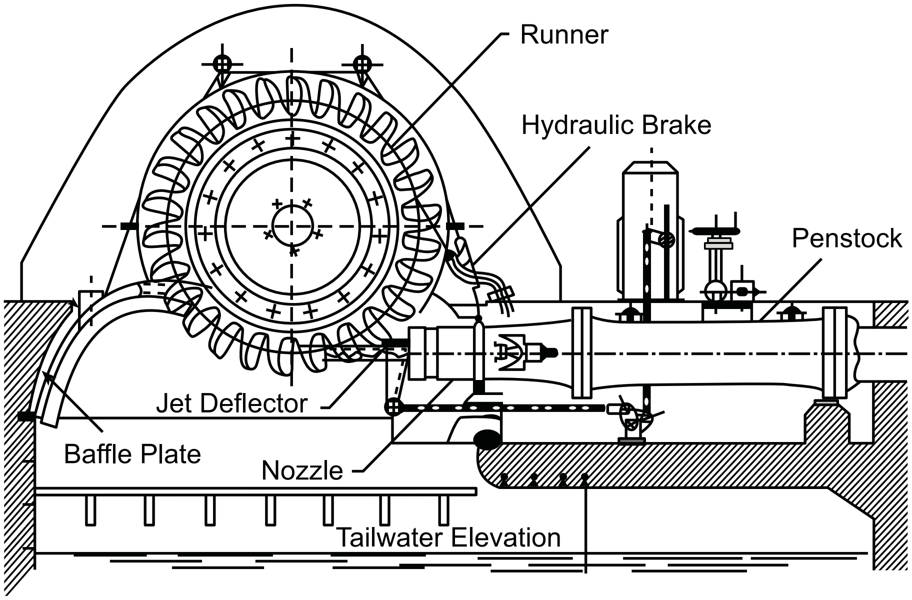

Fig. (2.1). Schematic diagram of Pelton Turbine contraction.

2.2. THEORY OF PELTON TURBINE

1. Turbine Power

Power input can be given by,

$$P_a = \gamma Q H_T \quad kW \tag{2.1}$$

where P_a is the available power measured in kW, H_T is the net head acting at the turbine inlet in m, and Q is the flow rate in m^3/s.

The supplied power by the turbine (kW) can be expressed as,

$$P_t = P_a \eta_t \tag{2.2}$$

where, P_t and η_t are the supplied power and turbine efficiency, respectively.

2. Discharge of the Nozzle and Jet Diameter

Fig. (**2.2**) shows a schematic diagram of the spear, nozzle, and jet components. The discharge depends on the least diameter of the jet that is precisely measured at the vena contraction. The discharge can then be expressed in terms of the diameter using the following relation,

$$Q = \frac{\pi}{4} {d_i}^2 V_1 \quad \textbf{(2.3)}$$

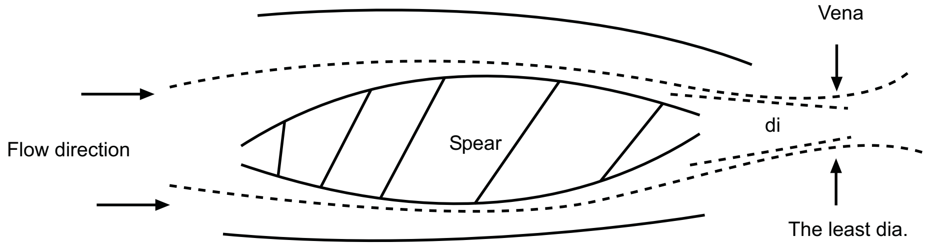

Fig. (2.2). Spear, nozzle, and jet.

d_i = The least diameter of the jet (m)

V_i = Velocity of the jet (m/s)

Q = Discharge (m^3/s)

$$V_i = C_V \sqrt{2gH} \quad \textbf{(2.4)}$$

C_V=Velocity coefficient

The least diameter can be calculated by solving Eqs. (2.3) and (2.4) together so that,

$$\therefore d_i = \sqrt{\frac{4Q}{\pi C_V \sqrt{2gH}}} \quad \textbf{(2.5)}$$

3. Multi Jets

The specific speed of Pelton turbine for a single jet and one runner (wheel) can be calculated by,

CHAPTER 3

Reaction Turbines

Abstract: In a reaction turbine, the runner utilizes both potential and kinetic energies. As flows through the stationary part of the turbine, the whole of its pressure energy is not transformed into kinetic energy and when the water flows through the moving parts, there is a change both in pressure and in the direction and velocity of flow of water. As the water gives up its energy to the runner, both its pressure and absolute velocity were reduced. The water, which acts on the runner blades is under a pressure above atmospheric and the runner passages are always completely filled with water.

The important reaction turbines are Francis and Kaplan which are discussed in this chapter according to their specification related to hydro–electric power plant. Theory for each type presented with sort notes and solved problems.

Keywords: Draft Tube, Flowrate through Reaction Turbine, Net Head, Reaction Turbine, Supply and discharge systems, Velocity Triangle.

3.1. TYPE OF REACTION TURBINE

In general, there are two types of reaction turbines, Francis and Kaplan turbines according to the direction of flow. The water enters the runner under pressure and flows over the vanes, the pressure head of water while flowing over the vanes, is converted into velocity head and finally reduced to the atmospheric pressure.

1. Francis Turbine: - it is an inward flow reaction turbine having radial discharge at the outlet. It is operating under a medium head and required medium quantity of water

Flow rate ≈ 2 → 800 m^3/s

Head ≈ 50 → 400 m

Net power up to ≈ 800 MW

2. Kaplan Turbine: - it is an axial flow reaction turbine in which the flow of water is parallel to shaft. A Kaplan turbine is used where a large quantity of water is available at a low head.

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Flow rate up to ≈ 1000 m^3/s

Head ≈ 40 m

Net power up to ≈ 200 MW

All parts of the Kaplan turbine such as spiral casing, guide mechanism and draft tube are similar as in Francis turbine system except:

The runner: the runner has two major differences. In Francis runner, the water enters radially while in Kaplan type it strikes the blades axially. The number of vanes in Francis turbines is 16 → 24 while in Kaplan it is only 3 → 6 vanes or at most 8 in an exceptional case. Thee RPM more than twice than that of Francis turbine.

Kaplan turbines have taken the place of Francis turbine for certain medium head installation [3].

3.2. CONSTRUCTION OF REACTION TURBINE

The turbine systems have the following component (Figs. **3.1** and **3.2**): -

1. **Penstock**: it is a waterway to carry water from the reservoir to the turbine casing. The Penstock section was manufactured in quarters and welded at the site (*e.g.* the penstock of Hydropower station in Venezuela is 7.5 m in diameters).

2. **Spiral Casing or Scroll Casing**: - to avoid losses of efficiency, the scroll casing is designed with a cross-sectional area reducing uniformly around the circumference, maximum at the entrance and nearly zero at the tip. This gives a spiral shape and hence the casing is named spiral casing.

3. **Guide Mechanisms**: - the Guide vanes or wicket gates are fixed between two rings known as guide wheel. The guide vane can be closed or opened to allowing a variable quantity of water according to the needs. The guide mechanism parts are: - Guide vanes, Guide wheel, regulating shaft, and Governor.

4. **Runner and Turbine Main Shaft**: - the aim of the runner is to guide the flow

inside the turbine. The width of the runner depends upon the specific speed. The runner may be classified as (i) slow (ii) medium (iii) fast, depending upon the specific speed. The runner is keyed to the shaft which may be vertical or horizontal.

5. **Draft Tube**: - the water after passing through the runner flows down through a tube called draft tube. It is generally drowned a proximately 1 m below the tail rase level. The advantage of it:
    a) It increases the head of water by an amount equal to the height of the runner outlet above the tail race.
    b) It increases the efficiency of the turbine [4].

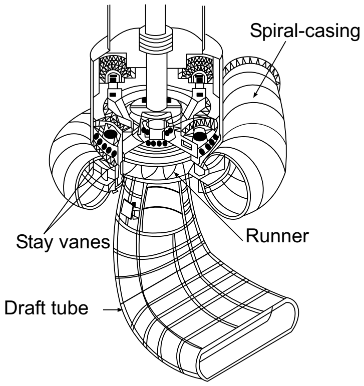

Fig. (3.1). Major Components of a Francis Turbine.

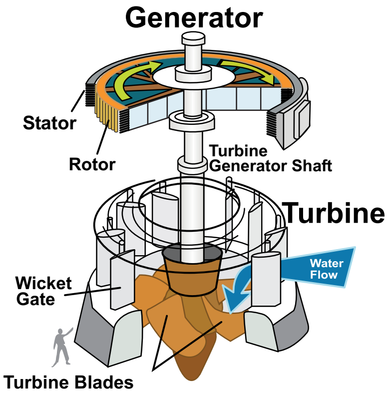

Fig. (3.2). Diagram of typical Kaplan Turbine.

CHAPTER 4

Similarity Laws for Turbine Specific Speed and Cavitations

Abstract: It is possible that a hydraulic machine will not give the desired result for which it has been designed. Such a machine is costly for manufacture and once it is made, it is difficult to change its components. Therefore, it is required to predict the performance of a prototype hydraulic machine before it is manufactured. This is done by making its model. Experiments are first performed on models from their results the performance of the prototype machine is predicted chapter on "Dimensional and Model Analysis" given in Fluid Mechanics will be useful for the prototype. Here prototype and its model are two similar machines having different specifications, which are to be compared. The concept of "Unit and specific Quantities" is a prerequisite for comparison of hydraulic machines. In addition, in this chapter a brief discussion about cavitation in turbine, turbine section, marking types of turbine and hydraulic turbine classification and section according to hydraulic power plants.

Keywords: Cavitation in turbines, Similarity laws, Turbines classification and selection.

4.1. SIMILARITY LAWS

Two similar hydraulic machines designed for different specifications are required to compare.

It is possible that a hydraulic machine may not give the desired results for which it has been designed. Such a machine is costly to manufacture and once it is made, it is difficult to change its components. Therefore, it is required to predict the performance of a prototype hydraulic machine before it is manufactured. This is done by making its model. The rate of flow, speed, power, *etc.* of hydraulic machines all functions of the working head which is one of the most fundamental of all quantities that go to determine the flow phenomena associated with machines such as turbines and pumps. For this reason, specific quantities are obtained by reducing any quantity to a corresponding unit head and some size such as the diameter of the runner for a reaction turbines and least jet diameter of Pelton turbines [1, 2].

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1- Specific Speed: it is the speed of identical turbine (geometrically similar and having same blade angle) working under the unit head and delivery unit power.

The concept of specific is very important in the study of turbines and pumps. It is a modern basis of scientific classification of turbines and pumps.

It has been shown in section (3.2) that the tangential velocity at the runner is

$$U_1 = \frac{\pi D_1 N}{60} \quad or\ U_1 \propto D_1 N$$

And

$$U_1 = \phi\sqrt{2gH} \ \ or\ U_1 \propto \sqrt{H}$$

$$\therefore\ \ ND_1 \propto \sqrt{H}\ \rightarrow\ D_1 \propto \frac{\sqrt{H}}{N} \qquad \textbf{(4.1)}$$

Also, the power developed by the turbine is

$$P_t = \gamma Q H_n \quad or\ \ P_t\ \alpha\ QH_n$$

And

$$Q = AV \quad and\ V = \varphi\sqrt{2gH}$$

$$\therefore\ \ Q \propto\ {D_1}^2\ \sqrt{H}$$

$$or\ \ P_t\ \alpha\ {D_1}^2\ \sqrt{H}.H$$

$$or\ \ P_t\ \alpha\ {D_1}^2 H^{3/2} \qquad \textbf{(4.2)}$$

From (**4.1**, **4.2**) substituting for D_1 we get

$$P_t\ \alpha \frac{H}{N^2} H^{\frac{3}{2}} \quad i.e\ \ P_t\ \alpha \frac{H^{\frac{5}{2}}}{N^2}$$

$$or\ N \propto \sqrt{\frac{H^{\frac{5}{2}}}{P_t}} \quad or\ \ N = N_s\sqrt{\frac{H^{\frac{5}{2}}}{P_t}}$$

$$\therefore N_s = \frac{N\sqrt{P_t}}{H^{\frac{5}{4}}} \tag{4.3}$$

$If\ \ P_t = 1\ kW\ and\ H = 1\ m\ then\ numerically$

$N_s = N\ Which\ called\ unit\ speed$

$P_t = power\ developed\ by\ the\ turbine\ kW$

$N = speed\ of\ the\ runner\ in\ rpm$

$H =\ net\ head\ \ m$

During the design of the turbine, the specific speed should be the same for the model and prototype, therefore:

$N_{sm} = N_{sp}$

$m = model\ \ ; p = prototype$

$\therefore\ from\ equ. 3,2\ for\ P_{tm}\ \&\ P_{tp}$

$$\frac{N_m}{N_p} = \frac{D_p}{D_m} \times \sqrt{\frac{H_m}{H_p}} \tag{4.4}$$

2- Specific Flow:

For reaction turbine

$$Q = \pi DBV_f$$

The dimensions D and B generally have linear relations with D_1 the runner diameter at the inlet and therefore, since

$$V_f \propto \sqrt{H}$$

CHAPTER 5

Centrifugal and Positive Displacement Pumps

Abstract: A pump is a machine that provides energy to a fluid in a hydraulic system. It assists to increase the pressure energy or kinetic energy, or both, in the fluid by converting the mechanical energy. The basic difference between a turbine and the pump, from a hydrodynamic point of view, is that in the former flow takes place from the high-pressure side to the low-pressure side, whereas in pump flow takes place from the low pressure forwards the higher pressure. Thus in a turbine, there is accelerated flow while in a pump the flow is decelerated. Accelerated flow throughout the hydraulic turbines is less subjected to turbulence therefore the runner passages are relatively short and high efficiency is available for this machine due to reduced values for the friction losses. Decelerated flow throughout the centrifugal pumps is sensitive to separation and vortices therefore impeller passages are relatively long and gradually increased in cross-section area for lowering the friction losses – "centrifugal pumps" efficiency is normally lower comparing to the turbines.

At the beginning of this chapter, one presents a classification of centrifugal pumps, reciprocating pumps – (Fig. **5.1**) and pump turbines. In addition, basic centrifugal pump theory and a brief analysis of the net positive suction head (NPSH) that are very useful for the design and selection of the pumps are detailed. In the next sections similarity laws, specific speed, cavitation and selection of the pumps are available. All these items are illustrated by solved problems.

Chapters on "similarity law, specific speed and cavitation and pumps section" acquiring great efficiency in using the tool of mathematics and at the solved problems are available.

Keywords: Cavitation in pump, Centrifugal pumps, Efficiencies, Force and Power, Head of the pump, Negative suction lift, NPSH required, NPSH, Positive Displacement Pumps, Positive suction lift, Pump Turbine, Reciprocating pump.

5.1. CENTRIFUGAL PUMPS

All types of pumps that depend on the change of momentum during the flow through an impeller across the blades are called centrifugal pumps (C.P.).

The basic principle of the C.P. is that the blades or impellers rotating inside a closed fitting housing draw the liquid into the pump through a central inlet opening and

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by means of centrifugal force or change in momentum in the liquid outward through a discharge outlet at the periphery of the housing. That means changing the kinetic head to pressure head. The general classification of pumps regarding the principle, kind of action upon liquid, motion of working members, and form of working members are shown in Fig (**5.1**).

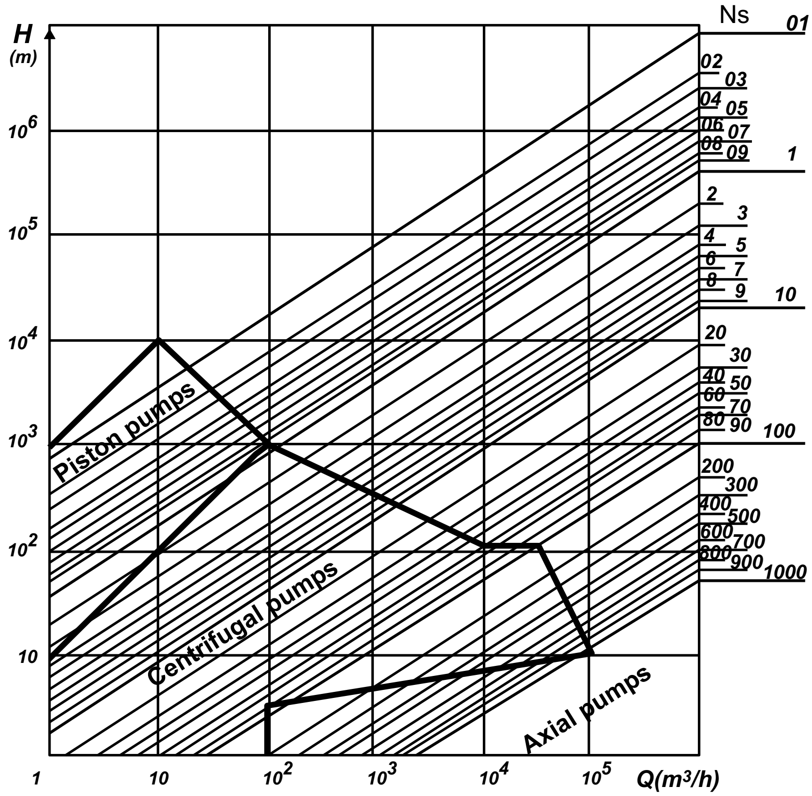

Fig. (5.1). Classification of pumps.

5.2. CLASSIFICATION AND STRUCTURE OF THE CENTRIFUGAL PUMPS

The basic classification of C.P. can consider the working head or hydraulic power of the machine.

1. Working Head - it is the head at which the liquid is delivered by the pump depending on the number of stages (Fig. **5.2** and Table **5.1**):

a) **Low lift centrifugal pumps**: are means to work against heads up to 15 m. impeller is surrounded by a volute and there are no guide vanes. The shaft is generally horizontal and water may enter the impeller from one or both sides depending upon the quantity of water to be delivered.

b) **Medium lift centrifugal pumps**: are used to build up heads as high as 40 m. they are generally provided with guide vanes. Water may enter from one or both sides depending on the quantity to be pumped.

c) **High lift centrifugal pumps**: are employed to deliver liquids at heads above 40 m. high lift pumps are generally multistage pumps because a single impeller cannot easily build up such high pressure. They may be horizontal or verticals the latter being used in deep wells.

Table 5.1. Type of pumps land and working head [4].

Types of Pumps	Working Head m	
Low lift C.P. Medium lift C.P.	Up to 15 15 → 40	} Single-stage
High lift C.P.	>40	Multistage

2. Hydraulic Power - is the absorbed power and represents the energy imparted on the fluid to increase its pressure and velocity, (Table **5.2**).

Table 5.2. Type of pump power and working head.

Types of Pumps	Working Head (m)
Very low C.P	up to 10
Low power C.P.	1 → 10
Medium power C.P.	10 → 100
High power C.P.	100 → 1000
Very high power C.P	>1000 m

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