Subject Name: **Turbo Machinery**

Subject Code: **ME-5001**

Semester: **5th**

THEORY NOTES - TURBO MACHINERY (ME 5001)

INTRODUCTION

A fluid machine is a device which converts the energy stored by a fluid into mechanical energy or *vice versa.* The energy stored by a fluid mass appears in the form of potential, kinetic and intermolecular energy. The mechanical energy, on the other hand, is usually transmitted by a rotating shaft. Machines using liquid (mainly water, for almost all practical purposes) are termed as hydraulic machines. In this chapter we shall discuss, in general, the basic fluid mechanical principle governing the energy transfer in a fluid machine and also a brief description of different kinds of hydraulic machines along with their performances. Discussion on machines using air or other gases is beyond the scope of the chapter.

CLASSIFICATIONS OF FLUID MACHINES

The fluid machines may be classified under different categories as follows:

Classification Based on Direction of Energy Conversion:

The device in which the kinetic, potential or intermolecular energy held by the fluid is converted in the form of mechanical energy of a rotating member is known as a *turbine.* The machines, on the other hand, where the mechanical energy from moving parts is transferred to a fluid to increase its stored energy by increasing either its pressure or velocity are known as *pumps, compressors, fans or blowers.*

Classification Based on Principle of Operation

The machines whose functioning depends essentially on the change of volume of a certain amount of fluid within the machine are known as *positive displacement machines.* The word positive displacement comes from the fact that there is a physical displacement of the boundary of a certain fluid mass as a closed system. This principle is utilized in practice by the reciprocating motion of a piston within a cylinder while entrapping a certain amount of fluid in it. Therefore, the word reciprocating is commonly used with the name of the machines of this kind. The machine producing mechanical energy is known as reciprocating engine while the machine developing energy of the fluid from the mechanical energy is known as reciprocating pump or reciprocating compressor.

The machines, functioning of which depend basically on the principle of fluid dynamics, are known as *rotodynamic machines.* They are distinguished from positive displacement machines in requiring relative motion between the fluid and the moving part of the machine. The rotating element of the machine usually consisting of a number of vanes or blades is known as rotor or impeller while the fixed part is known as stator. Impeller is the heart of rotodynamic machines, within which a change of angular momentum of fluid occurs imparting torque to the rotating member.

For turbines, the work is done by the fluid on the rotor, while, in case of pump, compressor, fan or blower, the work is done by the rotor on the fluid element. Depending upon the main direction of fluid path in the rotor, the machine is termed *as radial flow or axial flow machine.* In radial flow machine, the main direction of flow in the rotor is radial while in axial flow machine, it is axial. For radial flow turbines, the flow is towards the centre of the rotor, while, for pumps and compressors, the flow is away from the centre. Therefore, radial flow turbines are sometimes referred to as radially *inward flow machines* and radial flow pumps as radially outward flow machines. Examples of such machines are the Francis turbines and the centrifugal pumps or compressors. The examples of axial flow machines are Kaplan turbines and axial flow compressors. If the flow is party radial and partly axial, the term *mixed-flow machine* is used. Figure 1.1 (a) (b) and (c) are the schematic diagrams of various types of impellers based on the flow direction.

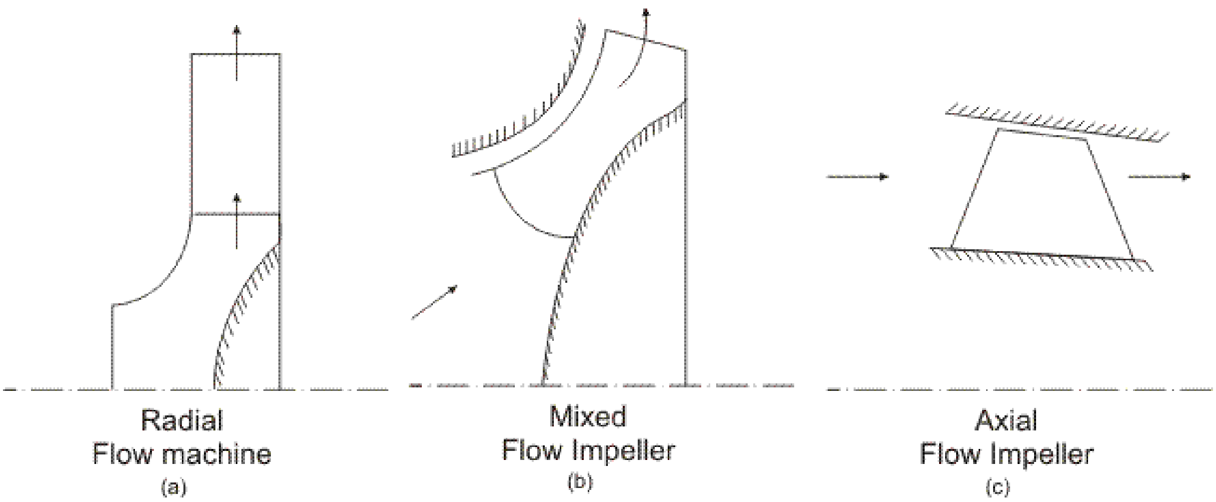

Figure: 1.1 Schematic of different types of impellers

CLASSIFICATION BASED ON FLUID USED

The fluid machines use either liquid or gas as the working fluid depending upon the purpose. The machine transferring mechanical energy of rotor to the energy of fluid is termed as a pump when it uses liquid, and is termed as a compressor or a fan or a blower, when it uses gas. The compressor is a machine where the main objective is to increase the static pressure of a gas. Therefore, the mechanical energy held by the fluid is mainly in the form of pressure energy. Fans or blowers, on the other hand, mainly cause a high flow of gas, and hence utilize the mechanical energy of the rotor to increase mostly the kinetic energy of the fluid. In these machines, the change in static pressure is quite small.

For all practical purposes, liquid used by the turbines producing power is water, and therefore, they are termed *as water turbines or hydraulic turbines.* Turbines handling gases in practical fields are usually referred to as *steam turbine, gas turbine, and air turbine* depending upon whether they use steam, gas (the mixture of air and products of burnt fuel in air) or air.

APPLICATION OF FIRST AND SECOND LAWS OF THERMODYNAMICS TO TURBO MACHINES

ROTODYNAMIC MACHINES

In this section, we shall discuss the basic principle of rotodynamic machines and the performance of different kinds of those machines. The important element of a rotodynamic machine, in general, is a rotor consisting of a number of vanes or blades. There always exists a relative motion between the rotor vanes and the fluid. The fluid has a component of velocity and hence of momentum in a direction tangential to the rotor. While flowing through the rotor, tangential velocity and hence the momentum changes.

The rate at which this tangential momentum changes corresponds to a tangential force on the rotor. In a turbine, the tangential momentum of the fluid is reduced and therefore work is done by the fluid to the moving rotor. But in case of pumps and compressors there is an increase in the tangential momentum of the fluid and therefore work is absorbed by the fluid from the moving rotor.

MOMENT OF MOMENTUM EQUATION AND EULER TURBINE EQUATION

Basic Equation of Energy Transfer in Rotodynamic Machines

The basic equation of fluid dynamics relating to energy transfer is same for all rotodynamic machines and is a simple form of "Newton's Laws of Motion" applied to a fluid element traversing a rotor. Here we shall make use of the momentum theorem as applicable to a fluid element while flowing through fixed and moving vanes. Figure 1.2 represents diagrammatically a rotor of a generalized fluid machine, with 0-0 the axis of rotation and the angular velocity. Fluid enters the rotor at 1, passes through the rotor by any path and is discharged at 2. The points 1 and 2 are at radii and from the centre of the rotor, and the directions of fluid velocities at 1 and 2 may be at any arbitrary angles. For the analysis of energy transfer due to fluid flow in this situation, we assume the following:

a. The flow is steady, that is, the mass flow rate is constant across any section (no storage or depletion of fluid mass in the rotor).
b. The heat and work interactions between the rotor and its surroundings take place at a constant rate.
c. Velocity is uniform over any area normal to the flow. This means that the velocity vector at any point is representative of the total flow over a finite area. This condition also implies that there is no leakage loss and the entire fluid is undergoing the same process.

The velocity at any point may be resolved into three mutually perpendicular components as shown in Fig 1.2. The axial component of velocity is directed parallel to the axis of rotation, the radial component is directed radially through the axis to rotation, while the tangential component is directed at right angles to the radial direction and along the tangent to the rotor at that part.

The change in magnitude of the axial velocity components through the rotor causes a change in the axial momentum. This change gives rise to an axial force, which must be taken by a thrust bearing to the stationary rotor casing. The change in magnitude of radial velocity causes a change in momentum in radial direction.

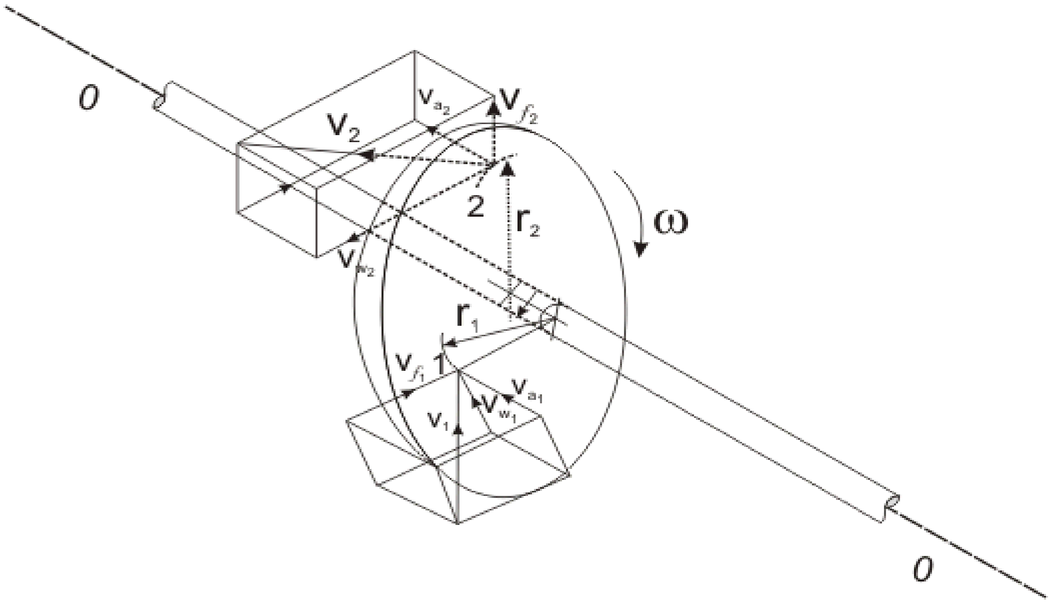

Figure 1.2: Components of flow velocity in a generalized fluid machine

However, for an axi-symmetric flow, this does not result in any net radial force on the rotor. In case of a non-uniform flow distribution over the periphery of the rotor in practice, a change in momentum in radial direction may result in a net radial force which is carried as a journal load. The tangential component only has an effect on the angular motion of the rotor. In consideration of the entire fluid body within the rotor as a control volume, we can write from the moment of momentum theorem:

$$T = m\left(V_{w_2} r_2 - V_{w_1} r_1\right) \quad \text{[Eq. 1.1]}$$

Where, *T* is the torque exerted by the rotor on the moving fluid, *m* is the mass flow rate of fluid through the rotor. The subscripts 1 and 2 denote values at inlet and outlet of the rotor respectively. The rate of energy transfer to the fluid is then given by:

$$E = T\omega = m\left(V_{w_2} r_2 \omega - V_{w_1} r_1 \omega\right) = m\left(V_{w_2} U_2 - V_{w_1} U_1\right) \quad \text{[Eq. 1.2]}$$

Where is the angular velocity of the rotor and which represents the linear velocity of the rotor. Therefore and are the linear velocities of the rotor at points 2 (outlet) and 1 (inlet) respectively (Fig. 1.2). The Eq, (1.2) is known as Euler's equation in relation to fluid machines. The Eq. (1.2) can be written in terms of head gained '*H*' by the fluid as:

$$H = \frac{V_{w_2} U_2 - V_{w_1} U_1}{g} \quad \text{[Eq. 1.3]}$$

In usual convention relating to fluid machines, the head delivered by the fluid to the rotor is considered to be positive and vice-versa. Therefore, Eq. (1.3) written with a change in the sign of the right hand side in accordance with the sign convention as:

$$H = \frac{V_{w_1} U_1 - V_{w_2} U_2}{g} \quad \text{[Eq. 1.4]}$$

COMPONENTS OF ENERGY TRANSFER It is worth mentioning in this context that either of the Eqs. (1.2) and (1.4) is applicable regardless of changes in density or components of velocity in other directions. Moreover, the shape of the path taken by the fluid in moving from inlet to outlet is of no consequence. The expression involves only the inlet and outlet conditions. A rotor, the moving part of a fluid machine, usually consists of a number of vanes or blades mounted on a circular disc. Figure 1.3a shows the velocity triangles at the inlet and outlet of a rotor. The inlet and outlet portions of a rotor vane are only shown as a representative of the whole rotor.

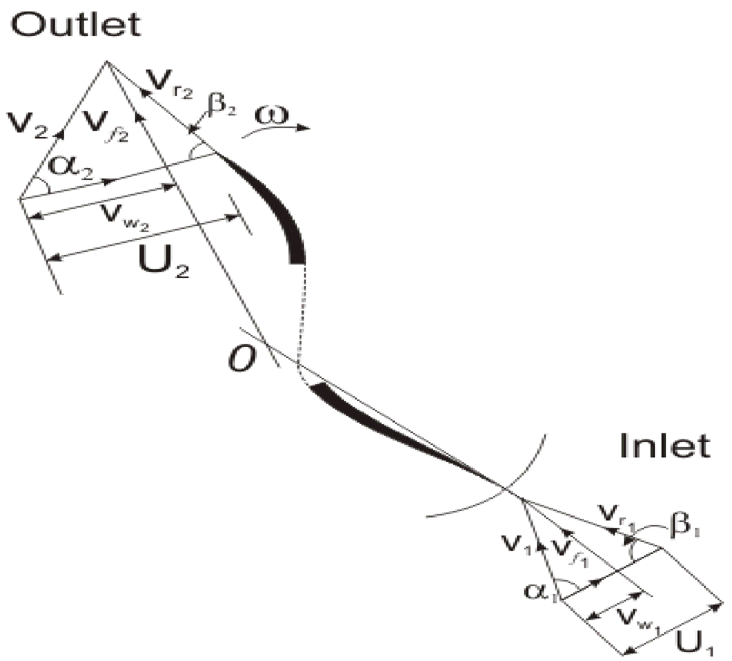

Figure: 1.3 (a)

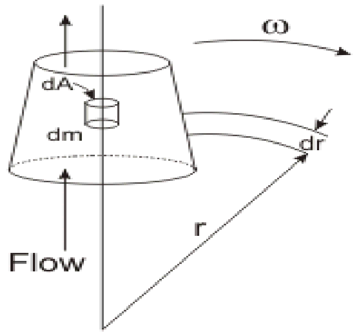

Figure: 1.3 (b)

Figure 1.3: Velocity triangles for a generalized rotor vane, Centrifugal effect in a flow of fluid with rotation.

Vector diagrams of velocities at inlet and outlet correspond to two velocity triangles, where U1 is the velocity of fluid relative to the rotor and are the angles made by the directions of the absolute velocities at the inlet and outlet respectively with the tangential direction, while and are the angles made by the relative velocities with the tangential direction. The angles α1 and α2 should match with vane or blade angles at inlet and outlet respectively for a smooth, shock-less entry and exit of the fluid to avoid undesirable losses. Now we shall apply a simple geometrical relation as follows:

From the inlet velocity triangle,

$$U_1 V_{w_1} = \frac{1}{2}(V_1^2 + U_1^2 - V_{r_1}^2) \quad \text{[Eq. 1.5]}$$

Similarly from the outlet velocity triangle.

$$U_2 V_{w_2} = \frac{1}{2}(V_2^2 + U_2^2 - V_{r_2}^2) \quad \text{[Eq. 1.6]}$$

Invoking the expressions Eq. (1.4), we get *H* (Work head, i.e. energy per unit weight of fluid, transferred between the fluid and the rotor as) as:

$$H = \frac{1}{2g}[(V_1^2 - V_2^2) + (U_1^2 - U_2^2) + (V_{r_2}^2 - V_{r_1}^2)] \quad \text{[Eq. 1.7]}$$

The Eq. (1.7) is an important form of the Euler's equation relating to fluid machines since it gives the three distinct components of energy transfer as shown by the pair of terms in the round brackets. These components throw light on the nature of the energy transfer. The first term of Eq. (1.7) is readily seen to be the change in absolute kinetic energy or dynamic head of the fluid while flowing through the rotor. The second term of Eq. (1.7) represents a change in fluid energy due to the movement of the rotating fluid from one radius of rotation to another.

More about Energy Transfer in Turbo-machines

Equation (1.7) can be better explained by demonstrating a steady flow through a container having uniform angular velocity ω as shown in Fig.1.3b. The centrifugal force on an infinitesimal body of a fluid of mass d*m* at radius *r* gives rise to a pressure differential d*p* across the thickness d*r* of the body in a manner that a differential force of d*p*d*A* acts on the body radially inward. This force, in fact, is the centripetal force responsible for the rotation of the fluid element and thus becomes equal to the centrifugal force under equilibrium conditions in the radial direction.

Therefore, we can write:

$$dp.dA = dm\,\omega^2\,r$$

With d*m* = d*A* d*r* ρ where ρ is the density of the fluid, it becomes

$$dp/\rho = \omega^2\,r\,d\,r$$

For a reversible flow (flow without friction) between two points, say, 1 and 2, the work done per unit mass of the fluid (i.e., the flow work) can be written as:

$$\int_1^2 \frac{dp}{\rho} = \int_1^2 \omega^2\,r\,dr = \frac{\omega^2 r_2^2 - \omega^2 r_1^2}{2} = \frac{U_2^2 - U_1^2}{2}$$

The work is, therefore, done on or by the fluid element due to its displacement from radius r_1 to radius r_2 and hence becomes equal to the energy held or lost by it. Since the centrifugal force field is responsible for this energy transfer, the corresponding head (energy per unit weight) is termed as centrifugal head. The transfer of energy due to a change in centrifugal head causes a change in the static head of the fluid.

The third term represents a change in the static head due to a change in fluid velocity relative to the rotor. This is similar to what happens in case of a flow through a fixed duct of variable cross-sectional area.

Regarding the effect of flow area on fluid velocity relative to the rotor, a converging passage in the direction of flow through the rotor increases the relative velocity and hence decreases the static pressure. This usually happens in case of turbines. Similarly, a diverging passage in the direction of flow through the rotor decreases the relative velocity and increases the static pressure as occurs in case of pumps and compressors. The fact that the second and third terms of Eq. (1.7) correspond to a change in static head can be demonstrated analytically by deriving Bernoulli's equation in the frame of the rotor.

In a rotating frame, the momentum equation for the flow of a fluid, assumed "inviscid" can be written as:

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} + 2\vec{\omega}\times\vec{v} + \vec{\omega}\times(\vec{\omega}\times\vec{r})\right] = -\nabla p$$

We assume that the flow is steady in the rotating frame so that. We choose a cylindrical coordinate system with z-axis along the axis of rotation. Then the momentum equation reduces to:

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} + 2\vec{\omega}\times\vec{v} + \vec{\omega}\times(\vec{\omega}\times\vec{r})\right] = -\nabla p$$

Then we can write

$$v\frac{\partial v}{\partial s}\vec{i}_s + v^2\frac{\partial \vec{i}_s}{\partial s} + 2\omega v\,\vec{i}_z \times \vec{i}_s - \omega^2 r\, i_r = -\frac{1}{\rho}\nabla p$$

More about Energy Transfer in Turbomachines

Taking scalar product with ρ it becomes

$$v\frac{\partial v}{\partial s} - \omega^2 r\frac{\partial r}{\partial s} = -\frac{1}{\rho}\frac{\partial p}{\partial s}$$

With a little rearrangement, we have

$$\frac{\partial}{\partial s}\left(\frac{1}{2}v^2 - \frac{1}{2}\omega^2 r^2 + \frac{p}{\rho}\right) = 0$$

Since *v* is the velocity relative to the rotating frame we can replace it by U. Further V_r is the linear velocity of the rotor. Integrating the momentum equation from inlet to outlet along a streamline we have

$$\frac{1}{2}(U_1^2 - U_2^2) + \frac{1}{2}(V_{r2}^2 - V_{r1}^2) = \frac{p_2 - p_1}{\rho} \quad \text{[Eq. 1.8]}$$

Therefore, we can say, with the help of Eq. (1.8), that last two terms of Eq. (1.7) represent a change in the static head of fluid.

ENERGY TRANSFER IN AXIAL FLOW MACHINES

For an axial flow machine, the main direction of flow is parallel to the axis of the rotor, and hence the inlet and outlet points of the flow do not vary in their radial locations from the axis of rotation. Therefore, the equation of energy transfer Eq. (1.7) can be written, under this situation, as:

$$R = \frac{\frac{1}{2g}[(U_1^2 - U_2^2) + (V_{r_2}^2 - V_{r_1}^2)]}{H} \quad \text{[Eq. 1.9]}$$

Hence, change in the static head in the rotor of an axial flow machine is only due to the flow of fluid through the variable area passage in the rotor.

RADIALLY OUTWARD AND INWARD FLOW MACHINES

For radially outward flow machine V_r and hence the fluid gains in static head. While, for a radially inward flow machine, V_2 and the fluid losses its static head. Therefore, in radial flow pumps or compressors the flow is always directed radially outward, and in a radial flow turbine it is directed radially inward.

PRINCIPLES OF IMPULSE AND REACTION MACHINES

Impulse and Reaction Machines The relative proportion of energy transfer obtained by the change in static head and by the change in dynamic head is one of the important factors for classifying fluid machines. The machine for which the change in static head in the rotor is zero is known as *impulse machine.* In these machines, the energy transfer in the rotor takes place only by the change in dynamic head of the fluid. The parameter characterizing the proportions of changes in the dynamic and static head in the rotor of a fluid machine is known as degree of reaction and is defined as the ratio of energy transfer by the change in static head to the total energy transfer in the rotor.

Impulse and Reaction Machines

For an impulse machine $R = 0$, because there is no change in static pressure in the rotor. It is difficult to obtain a radial flow impulse machine, since the change in centrifugal head is obvious there. Nevertheless, an impulse machine of radial flow type can be conceived by having a change in static head in one direction contributed by the centrifugal effect and an equal change in the other direction contributed by the change in relative velocity. However, this has not been established in practice. Thus for an axial flow impulse machine R=0. For an impulse machine, the rotor can be made open, that is, the velocity V_1 can represent an open jet of fluid flowing through the rotor, which needs no casing. A very simple example of an impulse machine is a paddle wheel rotated by the impingement of water from a stationary nozzle as shown in Fig.1.4.

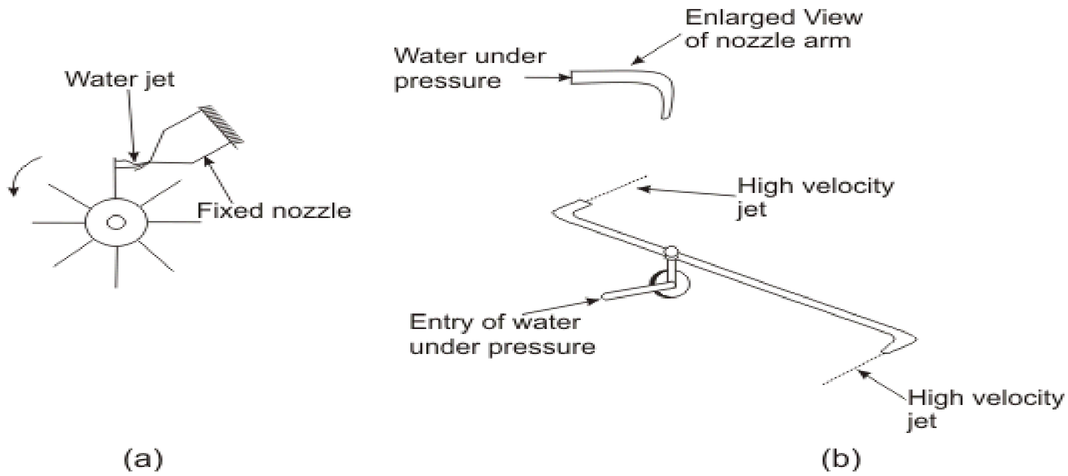

Figure 1.4: Pedal Wheel (Impulse Turbine) and Lawn Sprinkle (Reaction Turbine)

A machine with any degree of reaction must have an enclosed rotor so that the fluid cannot expand freely in all direction. A simple example of a reaction machine can be shown by the familiar lawn sprinkler, in which water comes out (Fig. 1.4 b) at a high velocity from the rotor in a tangential direction. The essential feature of the rotor is that water enters at high pressure and this pressure energy is transformed into kinetic energy by a nozzle which is a part of the rotor itself. In the earlier example of impulse machine (Fig. 1.4 a), the nozzle is stationary and its function is only to transform pressure energy to kinetic energy and finally this kinetic energy is transferred to the rotor by pure impulse action. The change in momentum of the fluid in the nozzle gives rise to a reaction force but as the nozzle is held stationary, no energy is transferred by it. In the case of lawn sprinkler (Fig. 1.4 b), the nozzle, being a part of the rotor, is free to move and, in fact, rotates due to the reaction force caused by the change in momentum of the fluid and hence the word ***reaction machine*** follows.

DEGREE OF REACTION

EFFICIENCIES

The concept of efficiency of any machine comes from the consideration of energy transfer and is defined, in general, as the ratio of useful energy delivered to the energy supplied. Two efficiencies are usually considered for fluid machines-- the hydraulic efficiency concerning the energy transfer between the fluid and the rotor, and the overall efficiency concerning the energy transfer between the fluid and the shaft. The difference between the two represents the energy absorbed by bearings, glands, couplings, etc. or, in general, by pure mechanical effects which occur between the rotors itself and the point of actual power input or output.

Therefore, for a pump or compressor,

$$\eta_{hydraulic} = \eta_h = \frac{\begin{array}{l}\text{useful energy gained by the fluid}\\ \text{at final discharge}\end{array}}{\text{mechanical energy supplied to rotor}} \quad \text{[Eq. 1.10 (a)]}$$

$$\eta_{overall} = \frac{\begin{array}{l}\text{useful energy gained by the fluid}\\ \text{at final discharge}\end{array}}{\begin{array}{l}\text{mechanical energy supplied to}\\ \text{shaft at coupling}\end{array}} \quad \text{[Eq. 1.10 (b)]}$$

For a turbine,

$$\eta_h = \frac{\text{mechanical energy delivered by the rotor}}{\text{energy available from the fluid}} \quad \text{[Eq. 1.10 (c)]}$$

$$\eta_{overall} = \frac{\begin{array}{l}\text{mechanical energy in output shaft}\\ \text{at coupling}\end{array}}{\text{energy available from the fluid}} \quad \text{[Eq. 1.10 (d)]}$$

