***Chapter Four***

***CENTRIFUGAL TURBOMACHINES***

***4-1.Introduction:***

The flow through a Centrifugal turbomachines is primarily in the radial direction, outward for a pump and usually inward for a turbine. Centrifugal turbomachines have thin raised curved radial surfaces attached to the face of a rotating disk. The unit, called ***an impeller***, rotates inside a ***casing*** or ***shroud***. At the outer edge of the impeller the shroud opens up into a ***scroll*** or ***volute***. ***Figure (4-1)*** shows the principle of a centrifugal turbomachine.



***Figure (4-1): Centrifugal Turbomachine.***

In a centrifugal pump the fluid enters axially at the ***center***, or ***eye***, of the impeller. The fluid then flows radially out through the passages on the face of the rotating impeller. The impeller increases the head of the flow by increasing both the static pressure and kinetic energy. The flow leaves the impeller and is diffused by passing through the annular space between the casing and the impeller. Sometimes a set of stationary diffusing vanes is located just outside the impeller. After being diffused, the high static pressure low kinetic energy flow is collected in the spiral volute or scroll.

The kinetic energy of a liquid coming out of an impeller is obstructed by creating a resistance in the flow. The first resistance is created by the pump casing which catches the liquid and slows it down. When the liquid slows down the kinetic energy is converted to pressure energy.

It is the resistance to the pump's flow that is read on a pressure gauge attached to the discharge line. A pump does not create pressure, it only creates flow. Pressure is a measurement of the resistance to flow. In Newtonian fluids (non-viscous liquids like water or gasoline) the term head is used to measure the kinetic energy which a pump creates. Head is a measurement of the height of the liquid column the pump creates from the kinetic energy the pump gives to the liquid.

The main reason for using head instead of pressure to measure a centrifugal pump's energy is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not. The pump's performance on any Newtonian fluid can always be described by using the term head.

***4-2.Basic Equations and Characteristic Curve:***

***Figure (4-2)*** shows the velocity triangle of the flow leaving the impeller. ***νr*** is the radial component of the absolute velocity from the velocity triangle:



***Figure (4-2): Velocity Triangle for Centrifugal Turbomachine.***

|  |  |
| --- | --- |
|  | …(4-1) |

The flow entering a centrifugal turbomachine has no tangential component of motion unless the flow first posses through a set of fixed guide vanes. In the absence of guide vanes:

|  |  |
| --- | --- |
| , | …(4-2) |

Then from ***equation (1-12)*** the head change across the blades is:

|  |  |
| --- | --- |
|  | …(4-3) |

The radial velocity can be related to the volume flow rate:

|  |  |
| --- | --- |
|  | …(4-4) |

Where ***b2*** is the width of the tip of the impeller

The capacity coefficient for a centrifugal turbomachine is:

|  |  |
| --- | --- |
|  | …(4-5) |

***Figure (4-3)*** shows the ideal characteristic curve of a centrifugal turbomachine which is ideal or similar to the axial-flow turbomachine. ***Positive*** ***ψ*** results in a ***pump*** and ***Negative*** ***ψ*** in a ***turbine***. The more common centrifugal turbine however, has inwardly directed flow.



***Figure (4-3): Ideal Characteristic Curve for Centrifugal Turbomachine.***

Blades with ***β2*** less than ***90o*** are called backward curved and results in a small head increase of the flow. Blades with ***β2*** equal to ***90o***are called radial and result in a head increase independent of the flow rate. Blades with ***β2*** greater than ***90o***are called forward curved and theoretically should result in a large head increase of the flow, ***Figure (4-4)*** show velocity triangle at the tip of the impeller for the three different kinds of blade curvature. The flow rate (radial velocity) and blade speed are the same for the three examples shown in ***Figure (4-4)***.

***Figure (4-4)*** clearly shows that as ***β2*** increases both the absolute velocity and its tangential component increase. The increase in tangential velocity means that the fluid head is increased. However, the increase in head is mainly in the form of kinetic energy, which must be converted into a static pressure rise by diffusing the flow in the pump casing. Diffusing processes are notoriously inefficient, so that the theoretically large head increase indicated for forward curved blades cannot actually be realized. Furthermore, the same stability arguments concerning the slope of the characteristic made for the axial flow pump are also valid for a centrifugal pump. Thus, for stability, ***β2***should be less than ***90o*** to give a negative slope characteristic, i.e., have backward-curved blades.



***Figure (4-4): Types of Blade Tip Curvature***

***a) Backward curved blades,β2<90o***

***b) Radial Blades, β2=90o***

***c)Forward Curved Blades,β2>90o***

***4-3.Behavior of Fluid in The Casing of The Centrifugal Pump:***

As indicted, the rotor of a centrifugal pump increases the pressure and the absolute fluid velocity of the fluid. The kinetic energy leaving the rotor is further converted into pressure in the pump casing. Let us use the basic angular momentum equation to examine the behavior of the fluid in the casing of the radial pump by assuming steady, frictionless flow, then equation becomes, in the absence of an externally applied torque:

|  |  |
| --- | --- |
|  | …(4-6) |





Inflow takes place at the surface area ***2***, while outflow occurs at the undesignated area as shown in ***Figure (4-5)***. Since we have radial flow symmetry, we can write the above equation:



***Figure (4-5): Schematic of Radial Pump Casing.***

|  |  |
| --- | --- |
|  | …(4-7) |

Inflow outflow

Or

|  |  |
| --- | --- |
|  | …(4-8) |

The preceding equation will again be recognized as representing free vortex flow. Hence the tangential component of the flow in the pump casing is free vortex flow. In addition, there is a radial component ***νr*** which satisfies the following relation derived from the continuity equation. The continuity equation is:

|  |  |
| --- | --- |
|  | …(4-9) |

Or

|  |  |
| --- | --- |
|  | …(4-10) |

From the velocity diagram of ***Figure (4-5)***, we obtain:



This relation states that the angle of inclination of the flow in the casing remains constant at all radii. The resulting flow patterns in the pump casing are shown in ***Figure (4-6)***.



***Figure (4-6): Flow Pattern in Pump Casing.***

***4-4.Pressure Change through the Casing of the Centrifugal Pump:***

The resulting change of pressure in the casing can be obtained by use of the Bernoulli equation, which becomes upon neglecting changes in elevation:



Substituting into the Bernoulli equation the expression for ***V*** obtained above:

|  |  |
| --- | --- |
|  | …(4-11) |

Then result:

|  |  |
| --- | --- |
|  | …(4-12) |

***4-5.Efficiencies of a Centrifugal Turbomachines:***

As mentioned in ***Chapter one***, ***section 1-4*** the definitions of the efficiencies for both turbines and pumps which is shown below:

***Hydraulic Efficiency:***

This is the efficiency with which water power is converted into diagram power and is given by:

|  |  |
| --- | --- |
|  | …(4-13) |

***Mechanical Efficiency:***

This is the efficiency with which the diagram power is converted into shaft power. The difference is the mechanical power loss.

|  |  |
| --- | --- |
|  | …(4-14) |

***Overall Efficiency:***

This is the efficiency relating fluid power input to shaft power:

|  |  |
| --- | --- |
|  | …(4-15) |

It's must be noted, that when we come to examine pumps, all the above expressions are inverted because the energy flow is reversed in direction with hydraulic efficiency converted into manometric efficiency, since all the energy given to the water is converted into pressure head, the head called manometric head.

***Example (4-1):***

A small centrifugal blower used for ventilation has a blade wheel with an inside diameter of ***0.1778 m***, outside diameter of ***0.2154 m***, and a constant blade width of ***0.127 m***. the blower turns at ***750 rev/min*** and discharges 9.9 m3/min of atmospheric air ***(ρ=1.20 kg/m3)*** through a ***12.7*** by ***15.24 cm*** rectangular exit to atmospheric pressure. The blower has no inlet guide vanes:

1. What are the inlet and outlet blade angles, ***β1*** and ***β2***.
2. What is the power input?
3. What is the static pressure change across the blades in m of water, neglect any frictional effects.



***Solution:***

Since there are no inlet guide vanes, the entering flow has no tangential component of motion, the entering flow is in the radial direction ***V1=νr1***. The blade wheel has a large number of thin closely spaced blades. We assume that the flow is completely guided by the blades and that the flow angles coincide with the blade angles. From the velocity triangle at the blade entrance:









To find ***β2*** from velocity triangle at exit ***(2)***



We find ***νθ2*** from the total head change



***ΔHi)1→2*** can be found by applying Bernoulli equation between room and outside (blower discharge ***3***):



Power input to the pump



The static pressure change across the blade is obtained by applying the Bernoulli equation between 1 and 2:



In terms of an equivalent column height of water:



***Example (4-2):***

A centrifugal water pump rotates at ***90 rad/sec***. The inlet radius of the impeller is **8 cm** while its outlet radius is ***16 cm***. The width of the impeller is ***5 cm***. The blade angles are ***β1=25.783o*** and ***β2=14.324o***, for smooth radial inflow and neglecting losses, determines the pump discharge, ideal change in total head ***ΔH***, pump power, and pressure rise in the impeller.

***Solution:***

Since the flow at inlet is radial so, the velocity triangle is





From the velocity diagram



The ideal change in total head



To find the velocity diagram at outlet we must find ***V2*** , β2 < 90o





To determine the pressure rise in the impeller:



So the ideal power is obtained from:



***Example (4-3):***

An outward flow reaction turbine has internal and external diameter of ***2.4 m*** and ***3 m***, respectively. The turbine has a radial discharge of ***6 m3/sec*** at outlet, and is running at ***200 rpm***, the total head on the turbine is ***40 m*** and width of the wheel at inlet is ***30 cm***, neglect thickness of the vanes, and find:

1. Velocity of the flow at inlet and outlet.
2. Velocity of whirl at inlet

***Solution:***



Since the turbine has a radial discharge at outlet, so ***V2=νr2***, ***α2=90***o

***Q=πD2b2νr2=πD1b1νr1***



***Example (4-4):***

An inward flow reaction turbine working under a head of ***8 m*** has guide vane angle ***25o*** and forward curved blade at ***105o***, assuming the velocity of flow to be constant and have radial discharge; determine hydraulic efficiency of the turbine.

***Solution:***

Since assumed velocity of flow being constant ***νr1=νr2***







***4-6.Francis' Turbine:***

The Francis wheel is an example of mixed impulse and reaction turbine which was designed by ***Francis*** ***James (1815-1892)*** it is mostly used in these days, for producing power under medium heads. They are adaptable to varying heads and flows and may be run in reverse as a pump. The Francis turbine is usually chosen when ***15≤ H ≤ 300 m.*** The largest Francis turbine of the world is at ***Krasnoyarsk*** producing ***690000 hp*** under a head ***95 m***. Another powerful Francis turbine is at ***Nohab***producing ***313000 B.H.P,*** under a head of ***100 m***.

The Francis' turbine is an inward flow device with the water entering around the periphery and moving to the center before exhausting. The rotor contained in a casing that spreads the flow and pressure evenly around the periphery, having radial discharge at outlet. The impulse part comes about because guide vanes are used to produce an initial velocity ***V1*** that is directly at the rotor. Pressure drop occurs in the guide vanes and the velocity is

***V1=kH1/2***

Where

***H*** is the head drop in the guide vanes.

***Example (4-5):***

A Francis' turbine, working under a head of ***14 m*** has guide blade angle of ***20o*** and radial vanes at inlet. The ratio of inlet and outlet diameters is ***3*** to ***2***. The velocity of flow of water at exit is ***4 m/sec***. Assuming the velocity of flow to be constant, determine the peripheral velocity at inlet and the vane angle at outlet.

***Solution:***





***Problems:***

***Q4-1:***

An inward flow reaction turbine has tangential velocity of runner, velocity of flow and velocity of whirl at inlet as ***30 m/sec***, ***3 m/sec***, and ***24 m/sec***, respectively. Assuming the discharge to be radial at outlet and hydraulic efficiency as ***78%***, determine the total head on the turbine and the inlet vane angle.

***Q4-2:***

A Francis' turbine has forward curved vane at inlet and discharges radially at outlet, if the velocity of flow is constant and equal to velocity of discharge from the suction tube. Show that the hydraulic efficiency can be expressed by:



Where ***θ1*** is the vane angle at inlet=***180-β1*** and ***α1*** guide blade angle.

***Q4-3:***

Calculate the vane angle at inlet of a centrifugal pump impeller having ***300 mm*** diameter at inlet and ***600 mm*** diameter at outlet. The impeller vanes are set backward at angle of ***45***o to the outer rim and the entry of the pump is radial. The pump runs at ***1000 r.p.m.*** and the velocity of flow through the impeller is constant at ***3 m/sec*** also calculate the work done by the water and the velocity, direction of water at outlet.

***Q4-4:***

An inward reaction turbine, with radial impeller blade at inlet and radial flow at outlet, show that the hydraulic efficiency is given by:



Where: ***α1*** is the guide blade angle at inlet; assume the velocity of flow to be remaining constant.

***Q4-5:***

A multi stage centrifugal is discharging ***45000 L/min*** of water against a manometric head of ***60 m***. There are four equal impellers keyed to the same shaft which is running at ***350 r.p.m.***. The vanes are curved back at an angle of ***60o*** to the tangent a the outlet periphery. The velocity of flow at outlet is ***0.27*** times the corresponding peripheral velocity, and the hydraulic losses in the pump are ***1/3*** of the velocity head at outlet of the impeller. Find the diameter of the impeller and manometric efficiency.

***Q4-6:***

A centrifugal pump has an impeller with inner and outer diameters of ***15 cm*** and ***25 cm***, respectively. It delivers ***50 L/sec*** at ***1500 rpm***. The velocity of flow through impeller is constant at ***2.5 m/sec***. The blades are curved back at an angle of ***30o*** to the tangent at exit. The diameters of suction and delivery pipe are ***15 cm*** and ***10 cm***, respectively. The pressure head at suction and delivery is ***4 m*** below and that at delivery is ***18 m*** above atmosphere. The power required to drive the pump is ***25 hp.***

Find i) the blade angle at inelt ii) the overall efficiency, and iii)Manometric (hydraulic) efficiency.

***Q4-7:***

The rotor of a centrifugal pump is ***175 mm*** diameter and runs at ***1450 rev/min***. It is ***15 mm*** deep at the outer and swept back at 30o. The inlet flow is radial; the vanes take up ***10%*** of the outlet area, ***65%*** of the outlet velocity head is lost in the volute chamber. The pump delivers ***0.015 m3/sec***. calculate

1- The head produced.

2- The efficiency.

3- The power consumed

***Q4-8:***

Show that the theoretical pressure rise through the impeller of centrifugal pumps has radial inlet flow and vanes are set backward at outlet, is given by:



if ***Δp:*** Pressure change(p2-p1)

***νr1:*** radial velocity component at inlet.

***νr2:*** radial velocity component at outlet.

***U1:*** peripheral velocity of impeller at inlet.

***β2:*** impeller angle at outlet***.(cosec2(β)=1+cot2(β))***