***Chapter Two***

***AXIAL FLOW TURBOMACHINES***

***2-1.Introduction:***

The flow through an axial flow turbomachine is primarily in the axial direction. Axial flow turbomachine have airfoil-shaped surfaces, called ***blades***, attached to the periphery of a rotating disk like spokes on a hub. The unit is known as ***rotor*** and is usually enclosed by casing to minimize leakage over the tips of the blades. The fluid flows axially through the annular space between the hub and casing. An example of the axial flow turbine is the Kaplan turbine which is usually chosen for heads of ***15 m*** or less. ***Figure (2-1)*** shows the principle of an axial flow rotor.



***Figure (2-1): Axial Flow Rotor.***

Many axial flow machines have sets of alternating moving blades and stationary surfaces called ***vanes***. The vanes are also airfoil-shaped and attached to the inside of the casing. A circumferential set of vanes is called ***stator***. The stator does not change the mechanical energy of the flow but simply alters the proportion between static and dynamic pressure. Since the fluid is confined, substantial changes in static pressure can occur. One rotor and its adjacent downstream stator are called a ***stage***. Some axial flow compressor may have as many as ***15*** stages; axial flow turbines usually have no more than three stages.

Axial flow compressor often have a set of fixed surfaces called ***inlet guide vane,*** at the entrance to the compressor to bring the flow at the proper angle on to the first stage rotor. ***Note*** that the annular area decreases in the direction of the flow because the air is being compressed and its density increased.

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

To focus our attention on a specific axial flow turbomachine, consider a stage of an axial flow compressor. The blade length is assumed small compared with the hub radius, and there are a large number of closely spaced thin blades and vanes.



***Figure (2-2): Stage Velocity Triangle.***

***Figure (2-2)*** shows the stage "Unrolled" and visualized as rows of blades and vanes and velocity triangle of the stage. The fluid leaves the stator of the previous stage with absolute velocity ***V1***, which makes an angle ***α1*** with the tangential direction. Since density changes are small across a single stage, continuity requires that the axial velocity be nearly constant

***υθ1=υθ2=υθ3=υθ4***

The rotor at ***1*** and ***2*** is the same

***U1= U2= U3= U4=ΩR***

The velocity triangles show an increase in ***υθ*** across the rotor; the rotor does work on the fluid. Across the stator, the kinetic energy is decreased ***(V32 < V22)*** and the static pressure increased. The stator acts as a diffuser to convert dynamic pressure into static pressure.

Using ***equation (1-12)*** to obtain the head change the across the rotor, we get



From the velocity triangles



And



Then,

|  |  |
| --- | --- |
|  | …(2-1) |

This is the total head change across the stage since there is no head change across the stator.

***Note*** that the relative velocity leaving the blades ***W2*** is drawn nearly tangent to the trailing edge of the blade.



Also, the absolute velocity vectors leaving the vanes, ***V1*** and ***V3***, are drawn nearly tangent to the trailing edge of the vanes.

 and 

This assumption is valid for very closely spaced very thin blades and vanes. Returning to ***equation (2-1)***, we divide through by ***U2/g***. The left-hand side of the equation is now dimensionless quantity ***g(ΔHi)1→2/U2***, which is called the ***head coefficient Ψ*** and is a measure of the total head change, since the *υa* used to determine the flow rate through the machine so the dimensionless velocity ration ***υa/U***, called the ***capacity coefficient Φ*** is a measure of the flow rate.

A plot of ***Ψ*** vs. ***Φ*** is called the ***characteristic curve*** of the turbomachine, ***equation (2-1)*** can be used to give the ideal characteristic curve of axial flow turbomachine. In terms of ***Ψ*** and***Φ***. ***Equation (2-1)*** becomes

|  |  |
| --- | --- |
|  | …(2-2) |

***Figure (2-3)*** shows a plot of ***equation (2-2)***



***Figure (2-3): Ideal Characteristic Curve for an Axial Flow Turbomachine.***

***Ψ*** is positive for pumps since they increase the head of the flow,***(ΔHi)1→2>0***; ***Ψ*** is negative for turbines since they extract work from the flow and decrease the head , ***(ΔHi)1→2<0***.

According to ***equation (2-2)***, the slope of the characteristic curve for an axial flow pump may be positive or negative, depending on the sign of the quantity ***(cot(β2)+cot(α1))***, as shown in ***Figure (2-3)***. As noted before ***α1, β2*** depend on the actual trialing edge angles of the vanes and blades. Pump operation stability requires that the characteristic curve have a negative slope.

This requirement can be simply demonstrated by considering ***what happens if a momentary partial blockage or resistance occurs***, causing the flow rate to decrease. For the pump to recover to its original flow rate it must increase the head or pressure of the flow to overcome the resistance. Increasing head for decreasing flow rate requires a negative characteristic. Similarity, if the flow rate fluctuated to a higher value, the head would decrease and the normal resistance of the system would cause the flow rate to drop to its original value. In stable operation deviation which returns the system to its original operating point.

***What happens if the pump has a positive characteristic and encounters momentary resistance which lowers the flow rate?***

The reduced flow rate results in a decreased head which is not even high enough to pump the original flow rate without the increased resistance. The increased resistance causes the flow rate to decreases further, causing a further drop in head, etc… The pump operation is unstable because there is mechanism to overcome the resistance and return the flow to its original operating condition.

***Figure (2-3)*** is a convenient way of presenting the performance of pumps. When using a pump, we are primarily interested in moving a given flow rate against a certain pressure resistance or increase in elevation, but when using a turbine, we are primarily interested in its power output and speed. Using ***equation (2-1)*** to give:

|  |  |
| --- | --- |
|  | …(2-3) |

The dimensionless quantity is called the ***Power Coefficient***. ***Figure (2-4)*** shows a plot of the ideal power coefficient versus the velocity ratio. When  is less than ***(1+cot β2 tan α1)***, the power is negative, indicating turbine operation;  greater than ***(1+cot β2 tan α1)*** results in positive power, or pump operation. Maximum turbine power output occurs at .



***Figure (2-4): Ideal Power Coefficient for an Axial Flow Turbomachine.***

Finally, since ***U1=U2***, the static pressure change across the rotor from Bernoulli's ***equation (1-21)*** is:

|  |  |
| --- | --- |
|  | …(2-4) |

The velocity triangle of ***Figure (2-2)*** show that ***W1 > W2*** because ***νθ2*** > ***νθ1*** and ***νa1=νa2***; that is, the static pressure increase across the rotor, the stator is stationary, ***U=0***, and no work is done on the flow. The Bernoulli ***equation (1-19)*** gives a static pressure change across the stator of

|  |  |
| --- | --- |
|  | …(2-5) |

From the velocity triangle of ***Figure (2-2)***, ***V2 > V3***, and the pressure rise across the stator. The stator acts as a diffuser.

***Example (2-1):***

A single stage axial flow pump takes water from a large reservoir. The pump has a hub diameter of ***0.9144 m*** and a tip diameter of ***1.2192 m***, turns at ***600 rev/min***, and delivers ***8.495 m3/sec***. of water. There are no inlet guide vanes. The trialing edge of the rotor blades makes an angle of ***30o*** with the tangential direction. The railing edge of the stator vanes is horizontal, i.e., it makes an angle of ***90o*** with the tangential direction. Neglecting frictional effects, calculate the static pressure change across the inlet, rotor, stator, and diffusing case. Assume that here are enough closely spaced thin blades vanes for flow angles to correspond to the actual blade and vane angles.



***Solution:***

In the inlet region there are no moving surfaces to do work on the fluid as shown in figure above. Furthermore, since there are no inlet guide vanes to import a tangential component of motion to the flow, assume the flow coming on to the rotor is purely axial. Then the axial velocity is the absolute velocity at ***1***, ***V1=νa***

Applying the Bernoulli equation between the reservoir and ***1*** gives



Where

P∞- is the pressure in the reservoir. The axial velocity is obtained from the flow rate



The axial velocity through the rotor and stator is the same because the annular cross sectional area does not change. The static pressure change across the inlet is:



The static pressure change across the rotor is calculated using Bernoulli's equation with a change in a total head due to moving blades, for an axial flow turbomachine ***U1=U2***, the relative velocities ***1*** and ***2***, ***W1*** and ***W2***, must be calculated. First, calculate the blade speed using he mean diameter of the annulus space, ***1.0668 m***.



From the velocity triangle at ***1*** (***Note*** that purely axial flow at ***1*** gives, ***(νθ1=0)***



From the velocity triangle at ***2***



The static pressure change across the stator is then



The stator vanes are stationary and do no work on the fluid. Their function is to diffuse the flow leaving the rotor, converting dynamic pressure into a static pressure increase; ***V2***is obtained from the velocity triangle at ***2***

 Since the triangle edge of the stator vanes are horizontal the flow leaves the stator with purely axial velocity, ***V3=νa ,*** then:



Finally, the static pressure change across the diffusing casing is also obtained by applying the Bernoulli equation between ***3*** and ***4***. The velocity downstream of the diffusing section ***V4*** is obtained from continuity.





The overall static pressure change the axial flow pump ***P4-P∞*** is



=111787.21+11068.873+146590.27-138248.92

=131197.43 N/m2

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

An axial flow fan operates at ***1200 rpm*** the blade tip diameter is ***1.1 m*** and the hub diameter is ***0.8 m***. The inlet and exit angles at the mean blade radius are ***30o*** and ***60o***, respectively. Inlet guide vanes give the absolute flow entering the first stage an angle of ***30o*** with the axial direction. There is no change in axial component of velocity across the rotor, for these idealized conditions, draw the inlet velocity diagram, determine the volume flow rate of the fan, and sketch the rotor blade shapes using the data so obtained, draw the outlet velocity diagram and calculate the minimum torque and power needed to drive the fan.

***Solution:***

The blade shape is shown above with inlet and outlet velocity diagram from continuity:



 and ***νa1=νa2 A1=A2***

Since at mean blade radius

 



From the geometry of inlet velocity diagram

⇒



⇒







***Problems:***

***Q2-1:***

A Kaplan turbine, operating under a net head of ***20 m*** develops ***50000 hps*** with an overall efficiency of ***86 %***. The speed ratio is ***2*** and flow ratio is ***0.6***. The hub diameter of the wheel is **0.35** times the outside diameter of the wheel. Find the diameter and speed of the turbine.

***Q2-2:***

An axial flow propeller turbine, the guide vanes are set at an angle of ***30o*** with respect to the radial direction. The inner radius of the guide vanes is ***1.7 m***; the vanes have a height of ***0.5 m***. The fluid velocity at the vanes is ***3 m/sec***. The turbine blades have a tip radius of ***0.8 m*** and a hub radius of ***0.18 m***. The rotor speed is ***30 rad/sec***. Determine the blade angles at the leading edge of the propeller blades.

***Q2-3:***

An axial flow fan has a tip diameter of ***2 m***, a hub diameter of ***0.8 m*** and rotates at ***1450 rev/min***, for the condition of zero inlet whirl estimate the velocity diagram at tip section, if the inlet absolute velocity is ***55 m/sec*** the air has a density of ***1.2 kg/m3*** and losses are ignored. Estimate also the fluid power, if ***Δp*** is ***5 kN/m2***.

***Q2-4:***

Axial flow turbo-machine driven at ***45 rad/sec***, if the energy change is ***120 J/kg***. Find the blade angle at inlet and outlet for both pumping and turbining modes of operation assuming ***νa=12 m/sec***, ignore efficiency, and assume zero inlet whirl for the pump and zero outlet whirl for turbine.

***Note:*** the blade tip and hub diameter are ***1500 mm***, ***600 mm***, respectively, then base your calculations on mean diameter.

***Q2-5:***

Show that the degree of reaction of a rotor in a frictionless flow through an axial flow pump with inlet guide vane is:  ****

where

***νa-*** Axial velocity component

***U-*** Pump velocity tangent in clockwise.

***α1-***The angle between the absolute velocity and the pump velocity at inlet.

***β2-***The angle between the relative velocity and the pump velocity at outlet.

***Q2-6:***

Kaplan turbines draws water from a large reservoir with surface head=***15 m*** above the inlet to the runner and discharges to atmospheric pressure. The turbine turns at ***140 rev/min*** at a flow rate of ***60 m3/sec***. The pertinent dimensions of the turbine are ***Dtip=3.75 m***, ***Dhub=1.5 m,*** ***Dg=7.5 m***, ***wg=1.5 m***, and ***αg=30o***. Determine the angles at the inlet and outlet of the blade ***β1*** and ***β2*** and estimate the power developed by the turbine.