Turbine, Generator & Auxiliaries - Course 334

THE STEAM TURBINE

The basic principle on which all steam turbines operate is that the heat energy which is possessed by the steam can be converted to kinetic energy of the steam. The heat energy of the steam is reduced and the velocity of the steam is greatly increased. If this high velocity steam is directed against a blade, the force exerted by the steam can be used to move the blade. The device used to convert the heat energy of the steam to kinetic energy is called a nozzle. Figure 1.1 shows how the high velocity steam leaving fixed nozzles can be used to move a series of blades. The steam can then be passed through a second set of fixed nozzles.

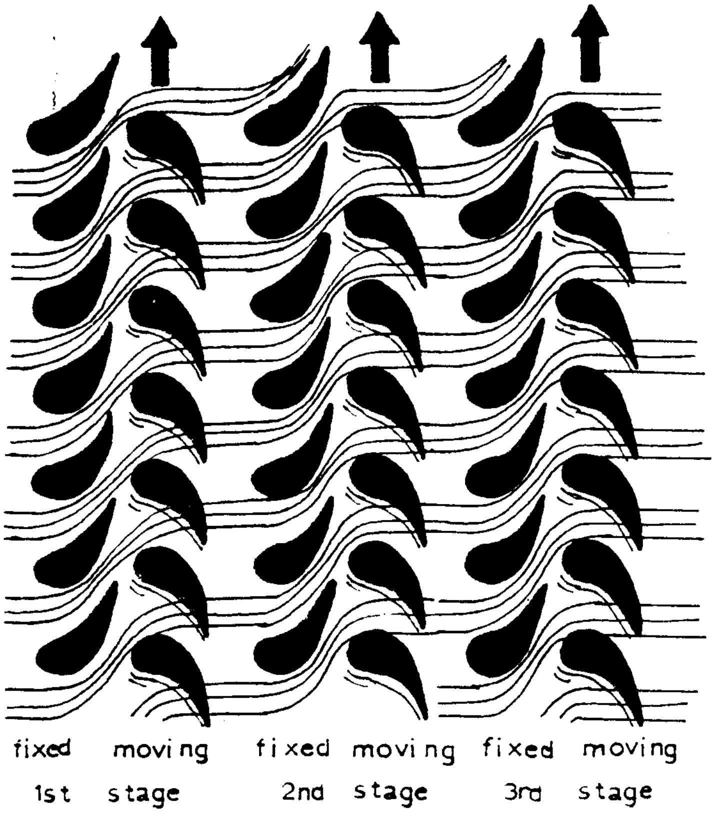


Figure 1.1

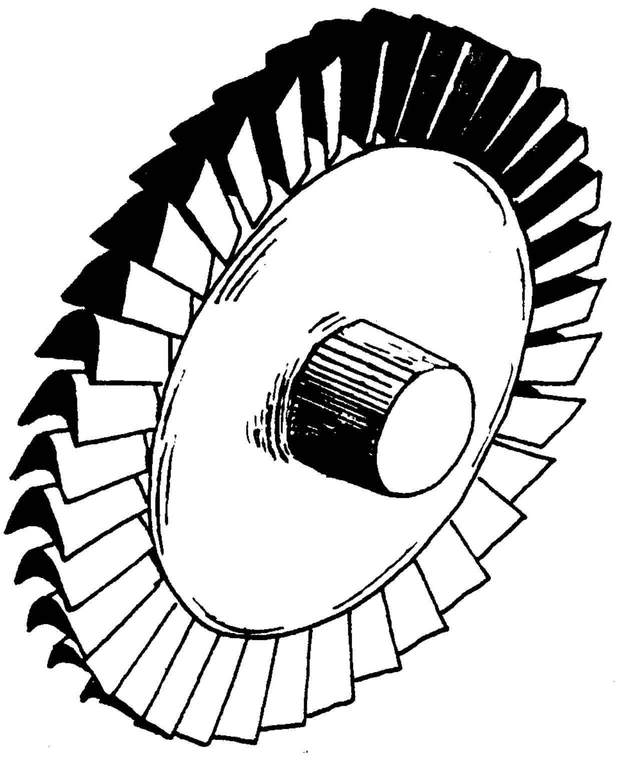


Figure 1.2

If the blades were arranged on a blade wheel such as shown in Figure 1.2, the high velocity steam leaving the nozzle could be used to turn the wheel. A set of fixed blade nozzles and moving blades is known as a stage and it is common to utilize a number of stages in a turbine to extract the useful heat energy in the steam.

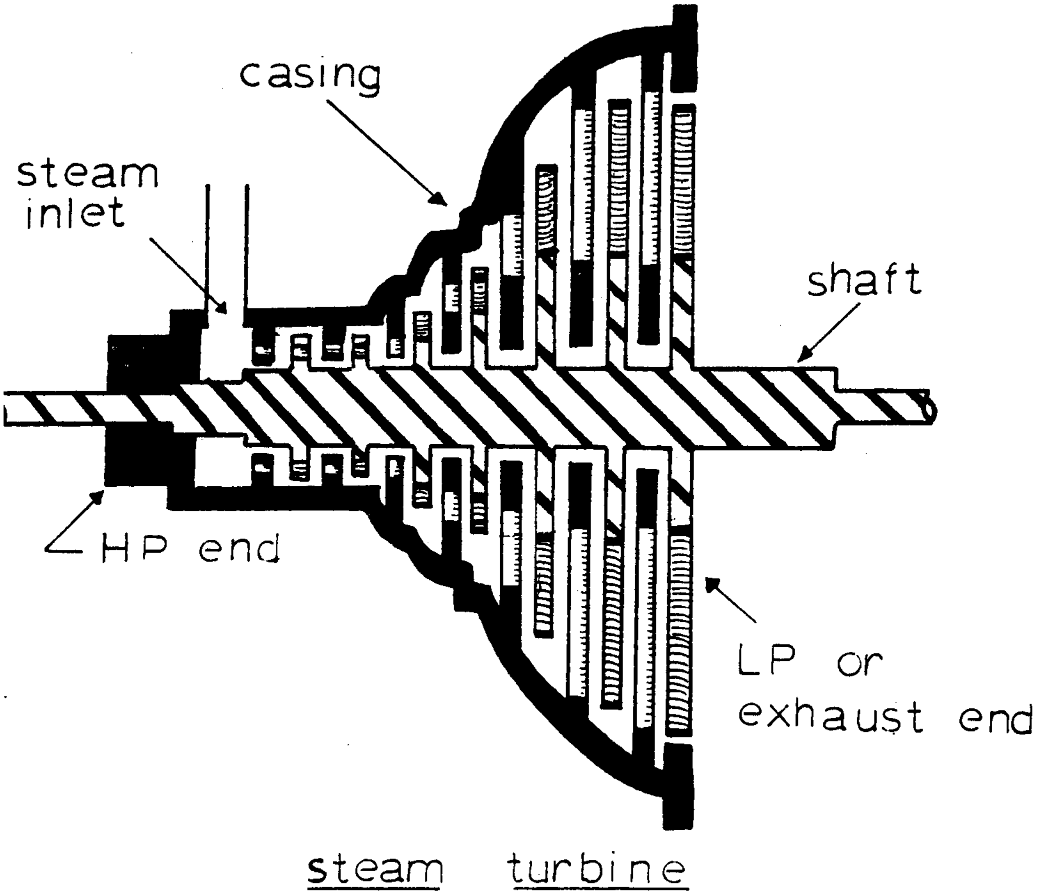


Figure 1.3

Figure 1.3 is a simplified section view of a turbine. The steam turbine consists of a single rotating shaft which has a number of blade wheels attached to it. The steam passing through the turbine is contained within a casing. The casing is usually split into an upper and lower half which are bolted together. This enables the upper half to be raised for maintenance. Attached to the casing are diaphragms which support the fixed blade nozzles. Figure 1.4 shows the construction of a typical diaphragm. The upper half is attached to the upper casing and the lower half to the lower casing. You will note that the turbine casing gets progressively larger as the steam goes from the high pressure end to the low pressure end. This is due to the expansion of the steam as the pressure is reduced. Steam entering the high pressure end of a modern nuclear turbine unit is typically around 250°C and 4000 kilopascals. At this temperature and pressure, one kilogram of steam occupies .05 cubic meters. The steam leaving the turbine unit and entering the condenser

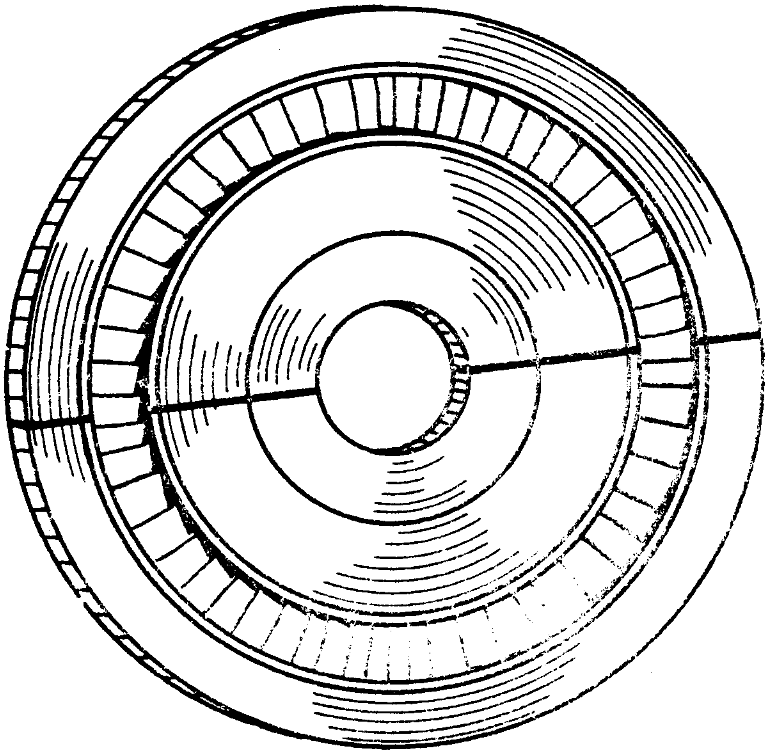


Figure 1.4

is typically around 35°C and 5.6 kilopascals. At this temperature and pressure, one kilogram of steam occupies 25.2 cubic meters. The steam expands roughly five hundred times from the inlet conditions to the exhaust conditions and provisions, such as increasing the casing size, must be made to handle this increased volume.

As the steam passes through the turbine, heat energy is converted to kinetic energy and the steam gives up a portion of its latent heat of vapourization. As this occurs, a portion of the steam condenses into minute water droplets which are carried along with the steam. When these droplets strike the moving blading, the effect is similar to sandblasting and the high velocity water droplets erode the turbine blading.

In addition, the presence of moisture in the steam passing through a turbine has a pronounced effect on turbine efficiency. Since the water droplets are not moving as fast as either the steam or the blades, the back side of the blades are continuously running into the water droplets. This results in a retarding force being exerted against the blades and decreases turbine efficiency.

Although modern turbines incorporate a number of features to remove the moisture within the turbine and to harden blading against moisture erosion, wet steam with greater than approximately 10% moisture cannot be tolerated. When the percent moisture reaches about 10%, the wet steam must be exhausted from the turbine. Unfortunately, with saturated steam at the inlet to the turbine, the steam reaches 10% moisture content before all of the useful heat energy is extracted from the steam. Because of this it is common to exhaust the steam from one turbine, pass the steam through a moisture separator where the moisture content of the steam is reduced to near zero, and then direct the steam into a second turbine. This second turbine usually exhausts to the condenser. While the steam is removed from the turbine for moisture separation, it is common to pass it through a reheater. This reheater superheats the steam going to the low pressure turbine by using main steam through a heat exchanger. This reheating of high pressure turbine exhaust steam improves the efficiency of the turbine unit. Figure 1.5 shows a section view of a turbine unit consisting of two turbines with a moisture separator and reheater between them.

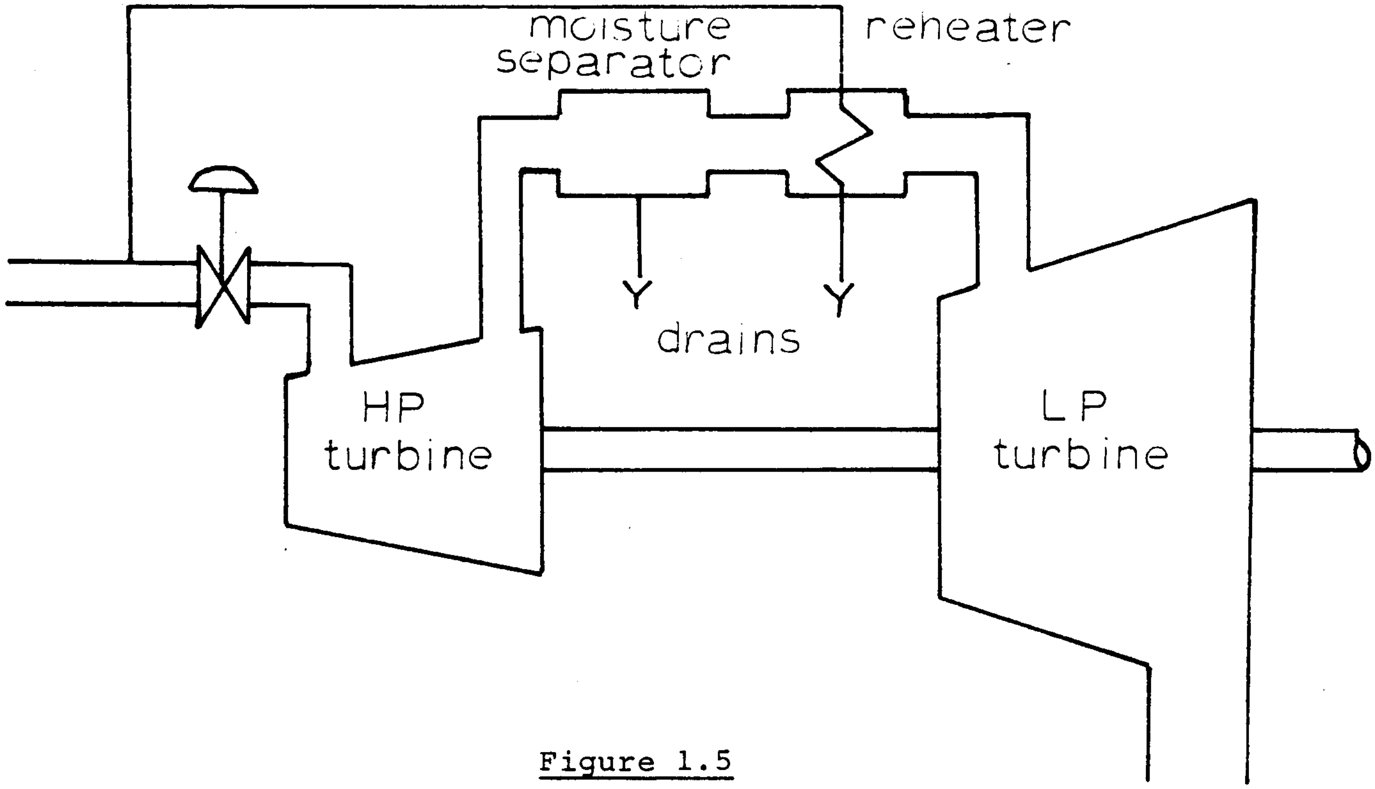


Figure 1.5

By convention, the turbine which receives steam directly from the steam generator is called a high pressure turbine or HP turbine. The turbine which exhausts to the condenser is called a low pressure turbine or LP turbine. The turbine unit shown in Figure 1.5 would be described as containing one high pressure turbine, a moisture separator, a reheater and one low pressure turbine.

Thus far, we have talked about turbines in which the steam enters at one end, expands through the turbine and exhausts at the opposite end. Such turbines are called single flow turbines because the steam flow is in one direction. Modern turbines may contain blading which allows substantial pressure drops across the moving blading. These large pressure drops tend to push the blade wheels from the high pressure side to the low pressure side. As steam flows become large and pressure drops across moving blading become significant, the force exerted on the rotor from the high pressure end may become difficult to handle. To account for this force, it is common to build double flow turbines such as shown in Figure 1.6.

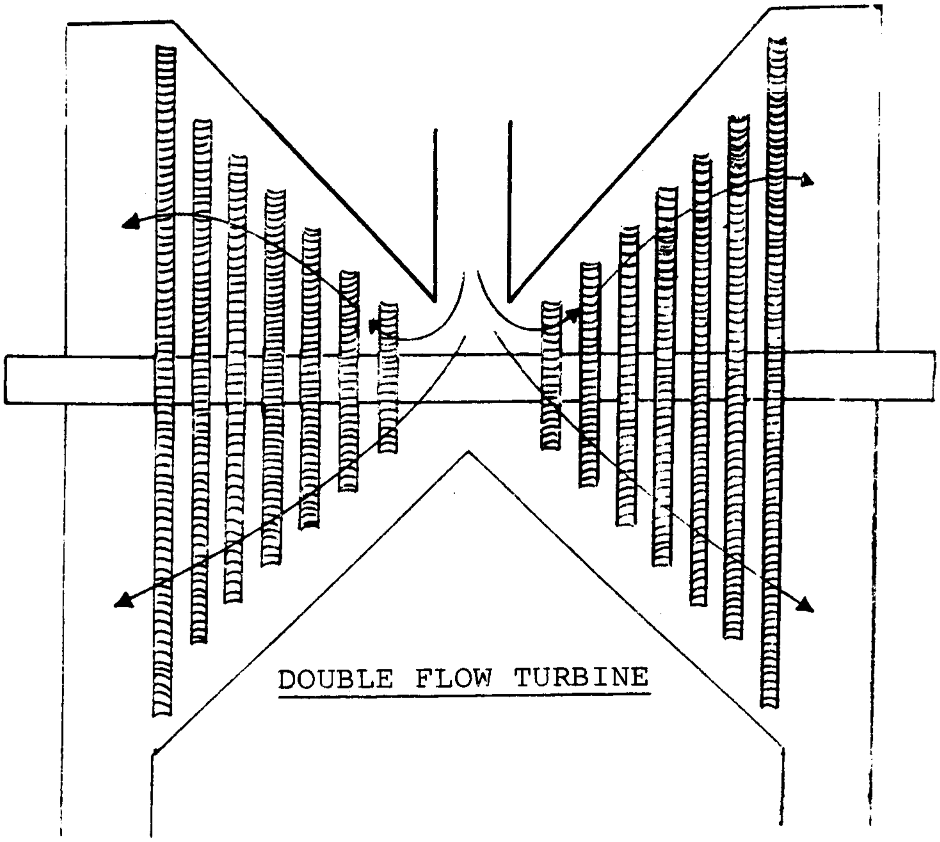


Figure 1.6

Steam enters the turbine in the middle of the casing and expands outward in both directions before exhausting at the ends of the turbine. In a double flow turbine, the force exerted by the pressure drop on one end of the rotor is exactly balanced by the force in the opposite direction exerted on the other end of the rotor. Double flow turbines are found in the majority of large turbine units.

Earlier, we discussed the extremely large increase in the volume of steam as it expanded through the turbine. In large turbines it is usually not possible to accommodate all of the steam in only one low pressure turbine. Normally one high pressure turbine will exhaust to two or more low pressure turbines. Figure 1.7 shows a turbine unit typical of those installed at Pickering or Bruce Generating Stations. In these turbine units, one double flow high pressure turbine supplies three double flow low pressure turbines. The arrangement of all the turbines in a turbine unit on a common shaft is known as a <u>tandem compounded</u> turbine unit. All turbine units in the Nuclear Generation Division of Ontario Hydro are tandem compounded.

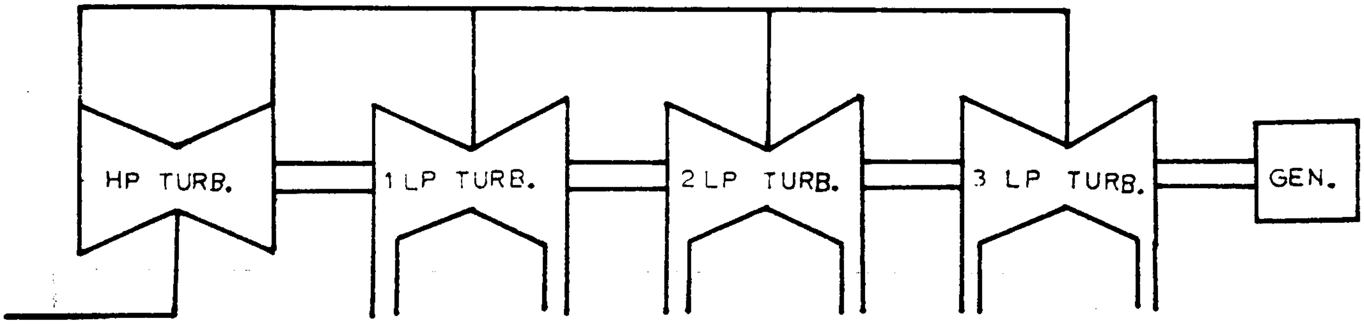
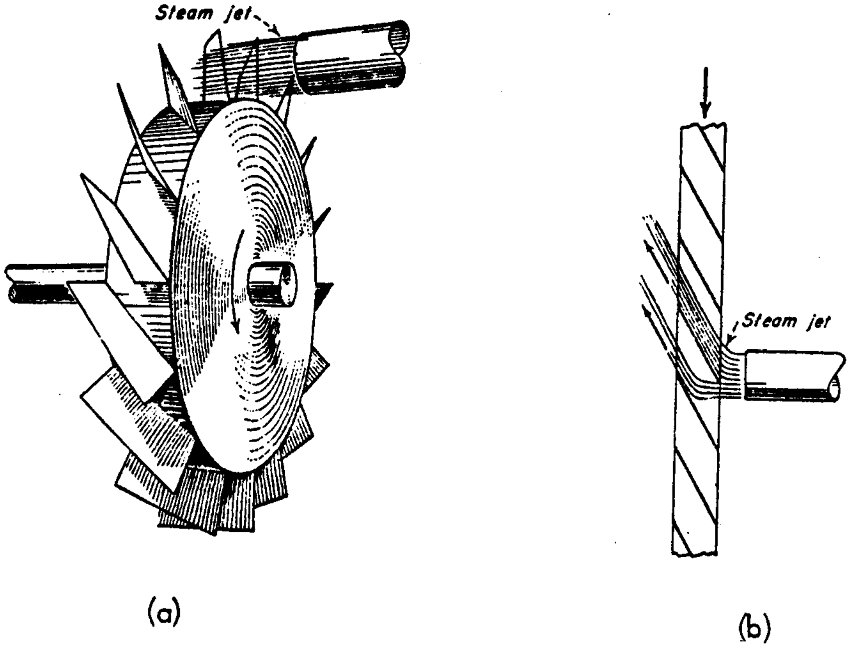


Figure 1.7

As mentioned earlier, the basic principle upon which all steam turbines operate is that the heat energy which is possessed by the steam can be converted to kinetic energy of the steam. The heat energy is reduced and the velocity is greatly increased. This high velocity steam can be used to turn a turbine wheel and create shaft mechanical power. Steam turbines can be divided into two principle types: reaction turbines and impulse turbines. The basic difference between the two types is in which part of the stage steam heat energy is converted to steam kinetic energy.

THE IMPULSE TURBINE

The first commercial steam turbine was manufactured in 1882 by Gustaf De Laval as a prime mover for a cream separator. The prime mover for De Laval's turbine was a single stage turbine with only one nozzle as is shown in Figure 1.8.



(a) (b)

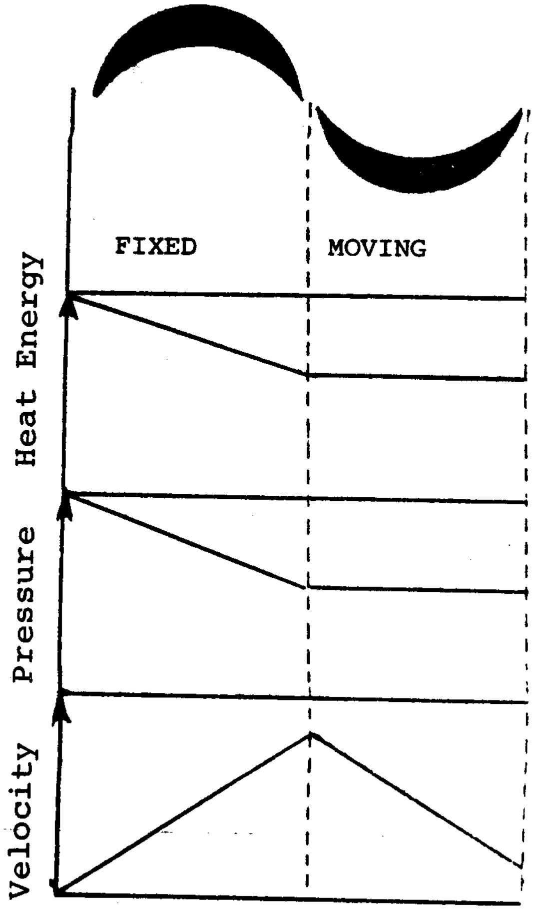
De Laval's Simple Impulse Turbine

Figure 1.8

The nozzle is shaped such that the heat energy of the steam is converted to kinetic energy. The high velocity steam is directed against the blades on the outer rim of a moving wheel. As the steam strikes the blades, they are moved out of the jet of steam. Changing the momentum of the steam delivers an impulse to the blade and the blade moves as a result of this impulse. Turbines which use this principle for converting steam kinetic energy to mechanical energy are called impulse turbines. Impulse stages of the type we are discussing are often called Rateau stages after their inventor.

What physically happens as the steam passes through one stage of an impulse turbine? One stage of an impulse turbine is shown in Figure 1.9. In the nozzle, the heat energy of the steam decreases and the steam velocity increases. Since pressure is one of the factors influencing the heat energy of the steam, the pressure decreases across the nozzle as the heat energy decreases.

In the moving blades, the high velocity of the steam is reduced as steam kinetic energy is converted to blade kinetic energy. The moving blade is shaped only to change the steam direction and so no conversion of heat energy to kinetic energy takes place in the moving blades. As a result, heat energy and pressure are constant across the moving blades of an impulse turbine.

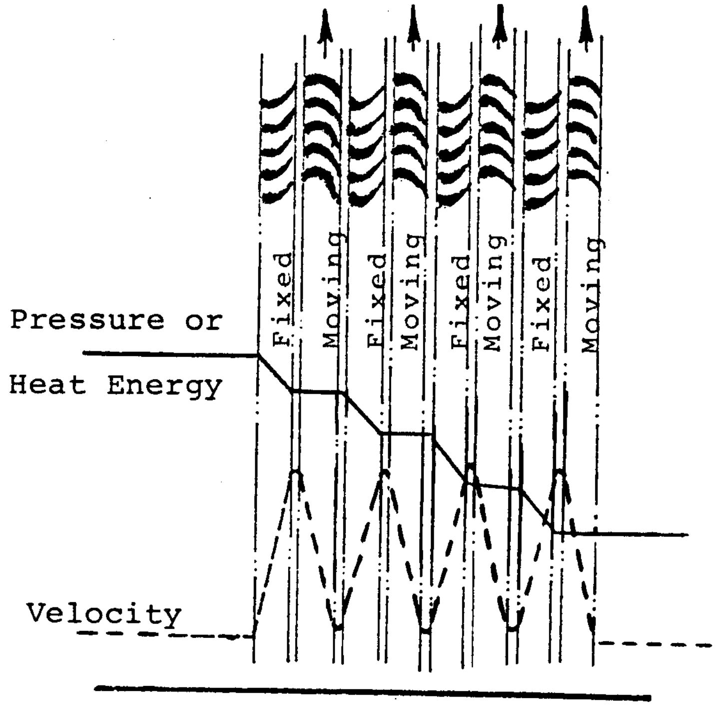


Impulse Stage

Figure 1.9

Although single stage turbines of the type De Laval manufactured are not uncommon, they are rather inefficient and as a result, are usually small. Turbines for use in large generating stations are constructed with many stages (ten to fifteen stages being typical). In addition, nozzles are usually mounted around 360° of the blade wheel so that power is delivered to the moving blades throughout the entire revolution.

Figure 1.10 shows the pressure, velocity and heat energy changes across a four stage impulse turbine. Note that since heat energy is converted to steam kinetic energy only in the nozzles, the heat energy and steam pressure decrease only in the nozzles.



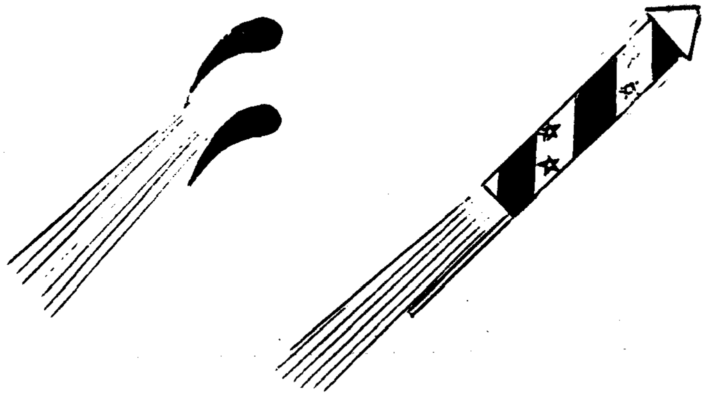
Four Stage Impulse Turbine

Figure 1.10

THE REACTION TURBINE

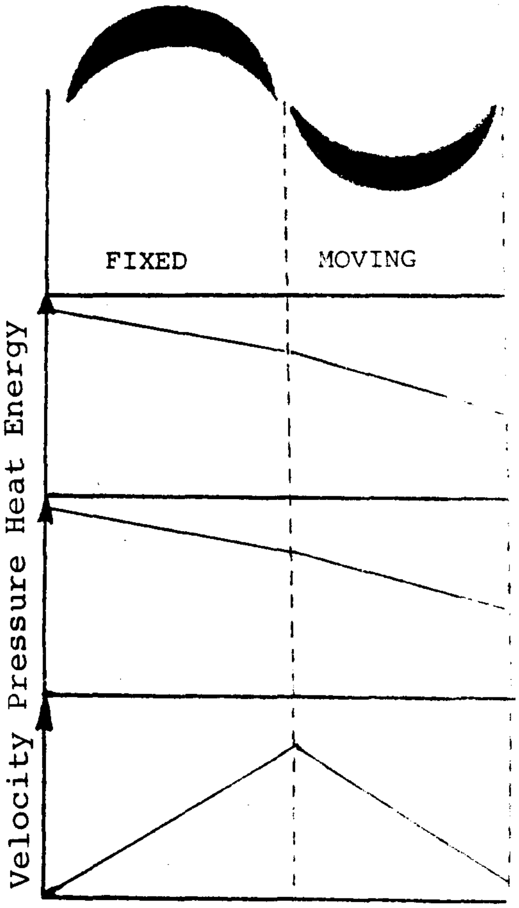
A few years after De Laval's development of the impulse turbine, Sir Charles A. Parsons developed the first reaction turbine. In the reaction turbine, the moving blades are shaped to allow the steam to expand as it leaves the moving blades. The blade moves away from the steam as a reaction to the steam expansion. The effect is exactly the same as a rocket moving in reaction to the expansion of gases.

In a practical reaction turbine, the moving blade is driven by a combination of this reaction effect and the impulse effect we have just examined. Since virtually all turbines utilize the impulse effect of high velocity steam to produce at least some of the force on the moving blades, the division between impulse and reaction blades is never very clear cut. Generally, if any force is produced by reaction, the stage is called a reaction stage. If no force is produced by reaction, the stage is called an impulse stage.



The Reaction Effect

Figure 1.11

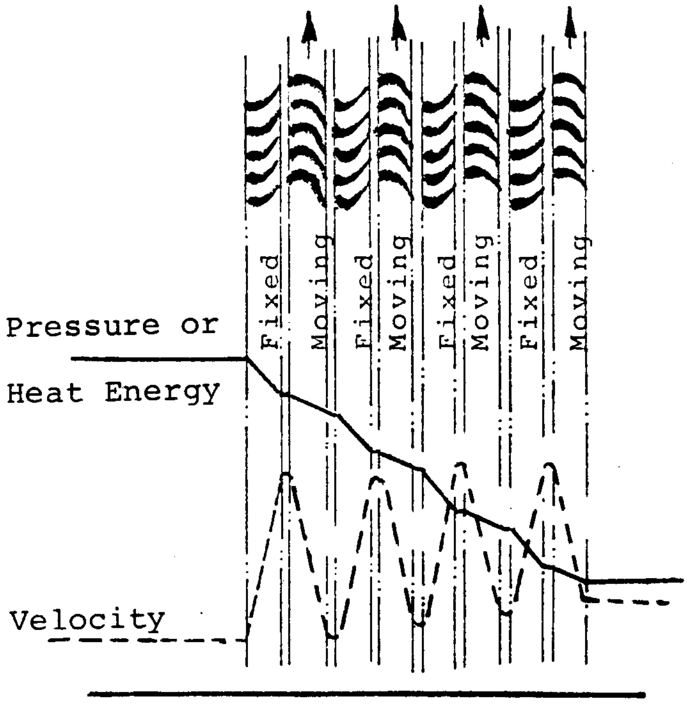


Reaction Stage

Figure 1.12

What physically happens as the steam passes through one stage of a reaction turbine? One stage of a reaction turbine is shown in Figure 1.12. The fixed blades are nozzles which work exactly as they do in the impulse stage. The heat energy and pressure of the steam decrease and the steam velocity increases. In the moving blades, the high velocity steam produces an impulse on the moving blades.

However, the shape of the moving blade allows steam expansion as the steam passes through this blading. This steam expansion lowers steam pressure and heat energy in the moving blade while the steam expansion produces a reaction effect and the blades move away from the expanding steam. In the reaction stage, steam heat energy is converted to steam kinetic energy in both the fixed and moving blades. In the impulse stage, steam heat energy is converted to steam kinetic energy in only the fixed blades.



Four Stage Reaction Turbine

Figure 1.13

Figure 1.13 shows the pressure, velocity and heat energy changes across a four stage reaction turbine. Note that since heat energy is converted to steam kinetic energy in both the fixed nozzles and moving blades, the heat energy and pressure decrease in both fixed and moving blades.

CHOICE OF TURBINE STAGE

The decision of which type of stage to use in a turbine is never clear cut. Each type of stage has its particular advantages and disadvantages and an application in which it is the superior choice.

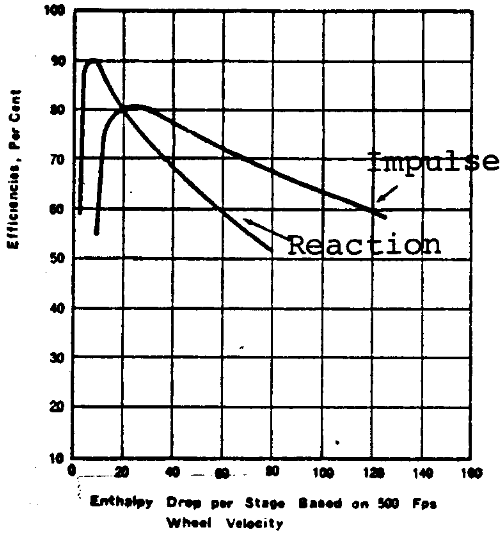


Figure 1.14

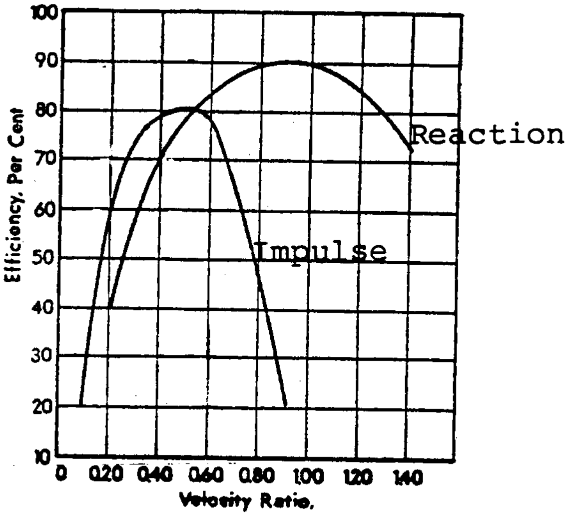


Figure 1.15

Efficiency and Energy Drop Per Stage: Figure 1.14 shows how the efficiency of a reaction turbine and an impulse turbine vary as the heat energy (enthalpy) drop per stage varies. If the enthalpy drop per stage is kept small, the reaction turbine is attractive due to its higher maximum efficiency. Typically, the number of stages in a reaction turbine is high to keep the enthalpy drop per stage low. In some instances, it is difficult to keep the enthalpy drop across a stage within the proper range for a reaction stage to give good efficiency. In these cases, an impulse stage is used to keep high efficiency with a large enthalpy drop.

Velocity Ratio: Velocity ratio is the ratio of how fast the blade is moving to how fast the steam is moving. Each type of stage has a different velocity ratio at which it runs most efficiently. Figure 1.15 shows the relationship between efficiency and velocity ratio. The impulse stage is most efficient when blade velocity is about one half of steam velocity. On the other hand, the reaction stage is most efficient when blade velocity is only slightly less than steam velocity.

As blade wheels become larger to accommodate the high volume of steam in modern large turbine units, the blade tangential velocity increases and the velocity ratio increases. As a result, the reaction turbine becomes more attractive since it develops its maximum efficiency at higher velocity ratios. Large turbines and particularly large low pressure turbines, are commonly reaction turbines.

Moisture Effects: Reaction turbines are more sensitive to the effect of water droplets decreasing efficiency by impact with the moving blades. Typically for a given percent moisture in the steam passing through a stage, the reaction turbine will suffer a loss in efficiency almost twice as great as an impulse turbine. In those turbines which encounter wet steam conditions such as the high pressure turbine in a nuclear unit, this fact has an influence on turbine design. One alternative is to make the HP turbine an impulse turbine. If, however, the HP turbine is a reactor turbine, the need to keep the moisture content low can be readily appreciated.

Axial Thrust: Reaction turbines have a pressure drop across the moving blades. Because of this, the force on the high pressure side of the blade wheel is greater than the counteracting force on the low pressure side. This force difference means there is a tendency of the wheel to move in the direction of decreasing pressure. In a single flow, high pressure reaction turbine, the cumulative force can be very large and the thrust bearing necessary to handle this force would be extremely large and costly. Although there are methods of compensating for this thrust in a single flow high pressure reaction turbine, the least complex method of handling axial thrust in a single flow turbine is to use impulse staging. Since the impulse stage has no pressure drop across the moving blades, it produces no axial thrust.

In a low pressure turbine, the pressure drop across the moving blades of a reaction turbine is much less. For a typical reaction nuclear steam turbine, the pressure drop across the moving blades of the HP turbine would be 200 kPa per stage while the pressure drop across the moving blades of the LP turbine would be 25 kPa per stage. It is possible to economically construct a thrust bearing which will handle the thrust of a single flow low pressure reaction turbine. The result is that while most single flow HP turbines have impulse blading, many single flow LP turbines have reaction blading.

PRESSURE GRADIENT THROUGH A TURBINE UNIT

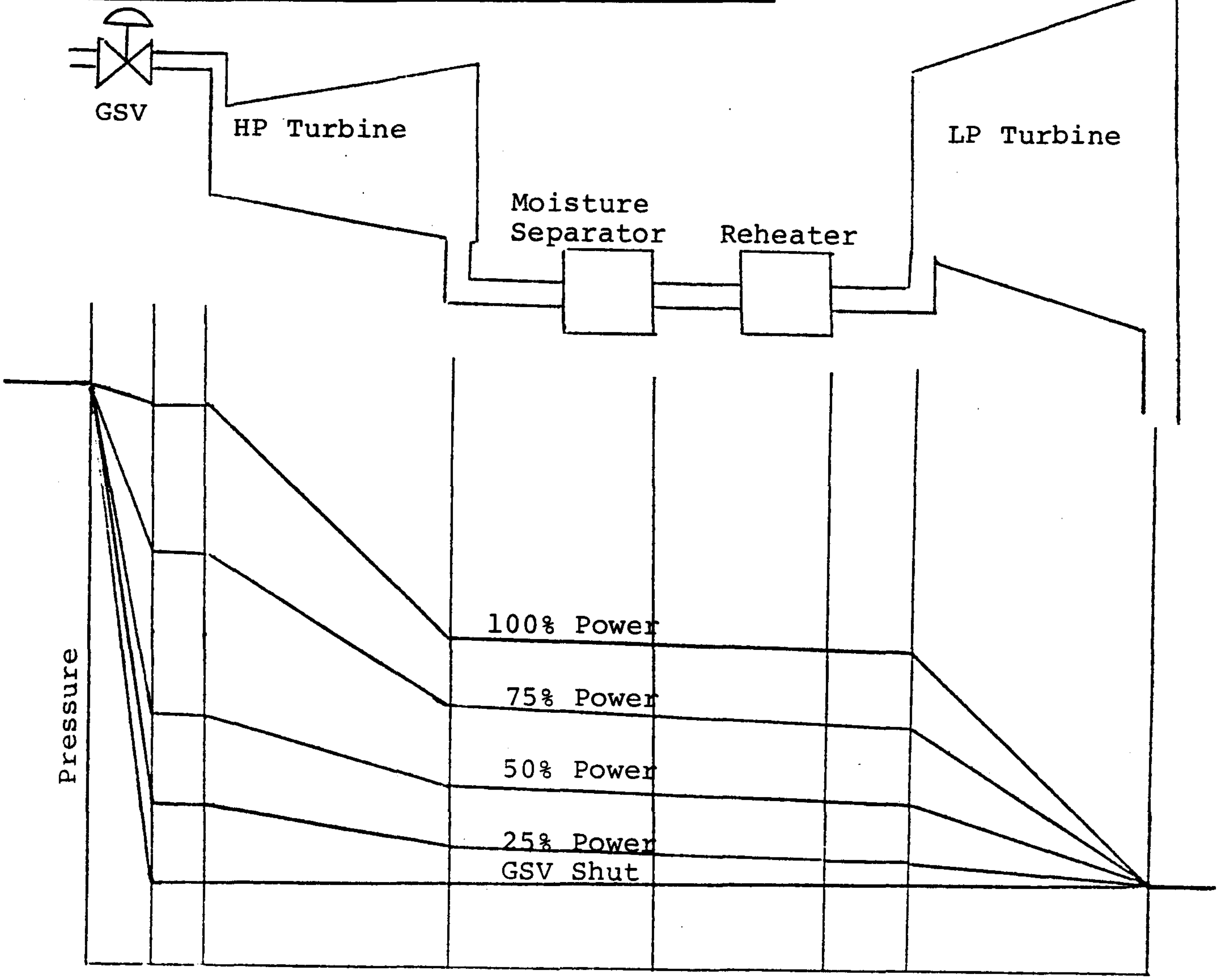


Figure 1.16

The turbine unit sits between two large vessels (the steam generator and the condenser) in which the temperatures and pressures are reasonably fixed. Between the steam generator and the condenser the temperature must drop from 250°C to 35°C and the pressure must drop from 4000 kPa(a) to 5.6 kPa(a).

Consider the case of a turbine unit such as shown in Figure 1.16. The turbine is shutdown and the condenser is being evacuated with the air extraction. Since there are no shut valves between the condenser and the steam admission valve, the turbine will be evacuated along with the condenser. With the steam admission valve shut, this valve has steam generator conditions on one side and the condenser vacuum on the other.

If the steam admission valve is cracked open to begin rolling the turbine, steam will begin to flow through the turbine. The pressure drop across a stage of a turbine is roughly proportional to the square of the steam flow through the stage. Thus at low steam flow rates, the pressure drop through the turbine will be very small and the majority of the pressure drop between steam generator and condenser will occur across the throttled steam admission valve.

As the turbine is brought up to operating speed, synchronized with the grid and loaded, the steam flow will increase. As the steam flow increases, the pressure drop through the turbine will increase. Since the pressure at any point in the turbine is equal to condenser vacuum plus the pressure drop from that point to the condenser, as steam flow increses the pressure throughout the turbine will increase. At the same time the pressure drop across the steam admission valve will decrease as the valve continues to be opened. The increase in the HP turbine first stage pressure is directly proportional to the increase in steam flow and as such, is an excellent indicator of turbine power. Typical pressure gradients for a large CANDU turbine unit are shown in Figure 1.16.

ASSIGNMENT

1. Identify and state the functions of the following turbine components:

   (a) casing
   (b) rotor
   (c) shaft
   (d) blade wheel
   (e) diaphragm
   (f) nozzle
   (g) fixed blade
   (h) moving blade

2. What is meant by the term "turbine stage"?

3. State the two principles by which steam kinetic energy is converted to blade kinetic energy and explain these principles.

4. Why are large power turbines multi-staged rather than having only one large stage?

5. Draw the pressure and velocity changes across a four stage impulse turbine.

6. Draw the pressure and velocity changes across a four stage reaction turbine.

7. Explain the difference between double flow and single flow turbines and explain the advantage of a double flow turbine.

8. What is the purpose of a steam nozzle?

9. The NPD turbine is a 25 MW turbine unit with a single flow HP turbine and a single flow LP turbine. Explain:

   (a) Why the HP turbine is an impulse turbine?

   (b) Why the LP turbine is a reaction turbine?

   (c) How the LP turbine can be single flow?

10. The Pickering NGS-A turbine is a 540 MW turbine unit with a double flow HP turbine and three double flow LP turbines. Explain:

    (a) Why the HP turbine has reaction blades?

    (b) Why the LP turbine has reaction blades?

    (c) Why the LP turbine is double flow?

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