NOTES & REFERENCES

Module 234-1

THE STEAM TURBINE

OBJECTIVES:

After completing this module you will be able to:

1.1 a) State the effect of turbine load on the turbine steam pressure profile. ⇔ ***Pages 3-4***

b) Explain the effect of turbine load on the performance of: ⇔ ***Pages 4-8***

i) The last stage(s);

ii) The remaining stages.

1.2 a) List four major adverse consequences of moisture in turbine steam. ⇔ ***Page 9***

b) Explain two reasons why moisture in turbine steam reduces turbine efficiency. ⇔ ***Pages 9-10***

c) Describe three types of erosion, and for each give one example of a typical component that may be damaged by it. ⇔ ***Pages 11-12***

d) Explain how wet steam promotes: ⇔ ***Pages 12-13***

i) General corrosion;

ii) Stress corrosion cracking or corrosion fatigue;

iii) Erosion-corrosion.

e) Explain how the presence of moisture in turbine steam increases turbine overspeed potential. ⇔ ***Page 13***

1.3 Describe five operational causes of excessive moisture content in turbine steam. ⇔ ***Page 14***

1.4 a) Describe two adverse consequences/operating concerns caused by excessive axial thrust. ⇔ ***Page 15***

b) Describe three causes of excessive axial thrust. ⇔ ***Pages 15-16***

c) List two indications of excessive axial thrust. ⇔ ***Pages 16-17***

1.5 Explain how the turbine power level affects the operation of the HP and LP turbine gland seals. ⇔ ***Pages 17-20***

1.6 State the major concern with all turbine seals. ⇔ ***Page 20***

NOTES & REFERENCES

1.7 Describe the adverse consequences/operating concerns caused by each of the following upsets:

Pages 20-21 ⇔ a) Rubbing in a turbine seal (3);

Pages 21-23 ⇔ b) Excessive gland sealing steam pressure (1);

Pages 23-25 ⇔ c) Insufficient gland sealing steam pressure (3).

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The previous turbine courses gave you the basic information about a typical steam turbine used in CANDU stations. You learned there about the major turbine components and the principle of turbine stage operation. You also learned how moisture in steam and axial thrust problems are dealt with during normal operation. And, you also located the major bearings and seals and learned how they operate.

This module covers the following topics with some emphasis placed on abnormal operating conditions and potential operational problems:

- Turbine operation at partial loads;
- Moisture in turbine steam;
- Excessive axial thrust;
- Turbine gland seal operational problems*.

* Other operational problems, such as thermal stresses, axial differential expansion and turbine vibration, are discussed in other modules.

What you will learn from this module will help you understand better the significance of some of the operational limitations imposed on the turbine and possible consequences of operating under abnormal conditions.

TURBINE OPERATION AT PARTIAL LOADS

This section describes the effects of turbine load on:

- The turbine steam pressure profile;
- Different performance of the last stage(s) as compared with the remaining stages of the turbine.

NOTES & REFERENCES

⇔ *Obj. 1 a)*

Turbine steam pressure profile

At partial loads, steam flow to the turbine is throttled by the governor valves*. As the steam flow rate is reduced, so is the turbine inlet pressure. Consequently, the interstage pressures are decreased as well. It turns out that, except for very small loads, all **interstage pressures are** pretty well **proportional to turbine load**, as shown in Fig. 1.1. For example, at 70% of full power, interstage pressures are about 70% of their value at full power. **The turbine outlet pressure** (approximately equal to condenser pressure) varies much less with turbine load and, for simplicity, **is assumed** here **to stay constant** over the whole load range. How the turbine inlet pressure changes with the turbine load depends, strictly speaking, on how the governor valves operate (in unison or sequentially) to control turbine load. For simplicity, Fig. 1.1 covers only the more common mode (used in nearly all CANDU stations) of the governor valves operating in unison. For this mode of valve operation, the turbine inlet pressure is approximately proportional to turbine load.

* In some stations, they are called *control valves* or *main control valves.*

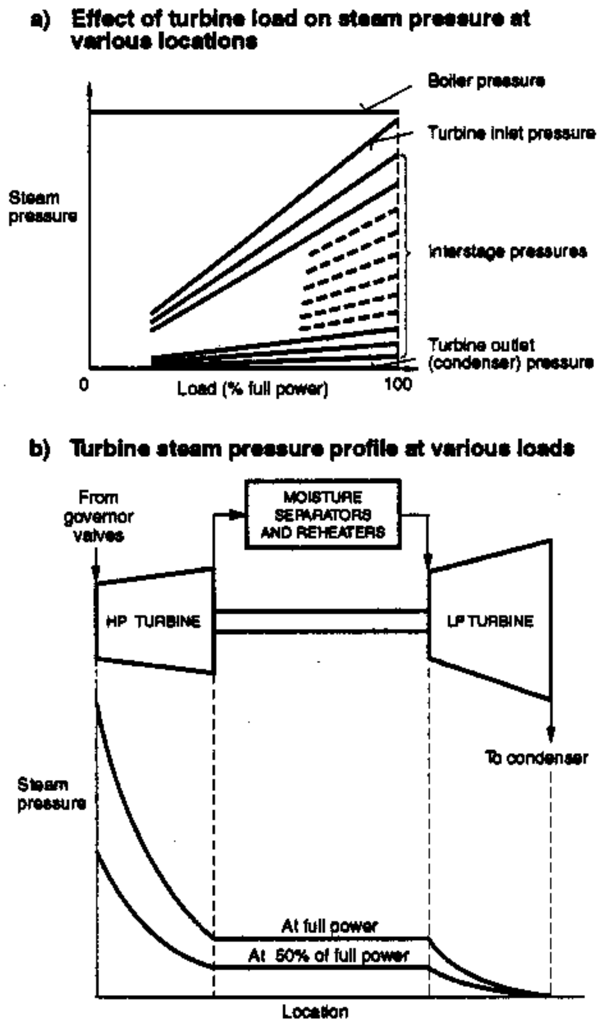

Fig. 1.1. Turbine steam pressure at various loads.

NOTES & REFERENCES

The proportional relationship between turbine load and interstage pressures is widely utilized in controlling the status of various isolating, drain or vent valves. For proper operation, these valves are required to open or close at certain turbine loads. Instead of measuring the load, turbine steam pressure (usually, in some extraction steam lines) is used to control the valve operation.

The other two reasons why you should know the effect of turbine load on the steam pressure profile along the turbine are:

1. Changes in the pressure profile affect the pressure and temperature of the available extraction steam and hence the **feedheating system performance**. This is covered in more detail in module 234-6.
2. The **performance of the turbine stages** can be affected when their inlet and outlet pressures change. This is explained in the following text.

Obj. 1 b) ⇔

Turbine stage performance – introduction

Let us first recall the principle of turbine stage operation. Briefly, the fixed blades accelerate steam and direct steam jets to the moving blades which are driven by the steam. During these processes, steam heat energy is converted first into steam kinetic energy and then into mechanical work by the rotor. Unfortunately, this conversion is not perfect because some heat turns into undesirable forms of energy (mainly frictional heat), generally referred to as losses.

The larger the losses, the less efficient the stage, and thus the whole turbine. To compensate for decreased efficiency, either more fuel must be "burned" in the reactor or the MW output must be reduced – both options being very costly, particularly in the long run. This is why we strive to maintain the turbine efficiency at a high level.

The effect of turbine load on the performance of various stages

There are many factors, eg. deposits on the blades or moisture in the steam, that can reduce the efficiency of a turbine stage. Among these factors, turbine load is very important because it can cause deterioration of the flow pattern in some turbine stages.

You may wonder what this term **flow pattern** means. In essence, it refers to the direction and velocity of the steam flow with respect to the turbine blades.

For efficient operation, the steam flow pattern must match the blade shape and velocity. If this condition is not met, efficiency

NOTES & REFERENCES

decreases. For example, this happens when the steam collides with the blades rather than flows smoothly over their surface.

Since the blade shape and velocity stay constant*, there is only one flow pattern that matches them in the best possible way. When this happens, the stage operates at the maximum efficiency. **Any deviation from this flow pattern must cause the stage efficiency to decrease.**

* The blade velocity changes only during turbine runup and rundown which are ignored here.

The flow pattern in a turbine stage depends on the steam velocity, and hence, its kinetic energy. Recall that this energy originates from heat. The less heat that is available per kilogram of steam, the slower the steam flows.

When the available heat is greatly reduced, the **steam moves too slowly to be able to drive the moving blades**. Worse than that, the steam retards the blade motion. Churning of the steam by the blades produces frictional heat, commonly referred to as **windage losses**. Note that these losses can be substantial due to the high velocity* of the moving blades. Since the steam retards the blade motion, **the stage must be driven**, either by the other stages of the turbine or by the generator (during motoring).

* In the last stage, with the longest blades, this velocity can reach 500 m/s at the blade tip!

How is all of this associated with turbine load? It turns out that turbine load affects the amount of heat that is available per kilogram of the steam. Recall that with decreasing turbine load, the turbine inlet pressure drops, while the exhaust pressure stays approximately constant. Therefore, **the lower the turbine load, the less heat is available** from each kilogram of steam. However, the effect is not distributed uniformly between all the stages. Instead, it occurs only **in the last few stages**. The reason for this is explained below.

First of all, the amount of heat available to a turbine stage depends on its inlet and outlet pressures. Note that the amount of this heat decreases when the inlet pressure drops and/or the outlet pressure rises. But what is the effect on this heat when both these pressures increase or both decrease as turbine load changes? The answer to this question is given in Fig. 1.2 on the next page where a simplified Mollier diagram is used to show the amount of heat available (Δh_{av}) to various turbine stages operating at different steam pressure.

NOTES & REFERENCES

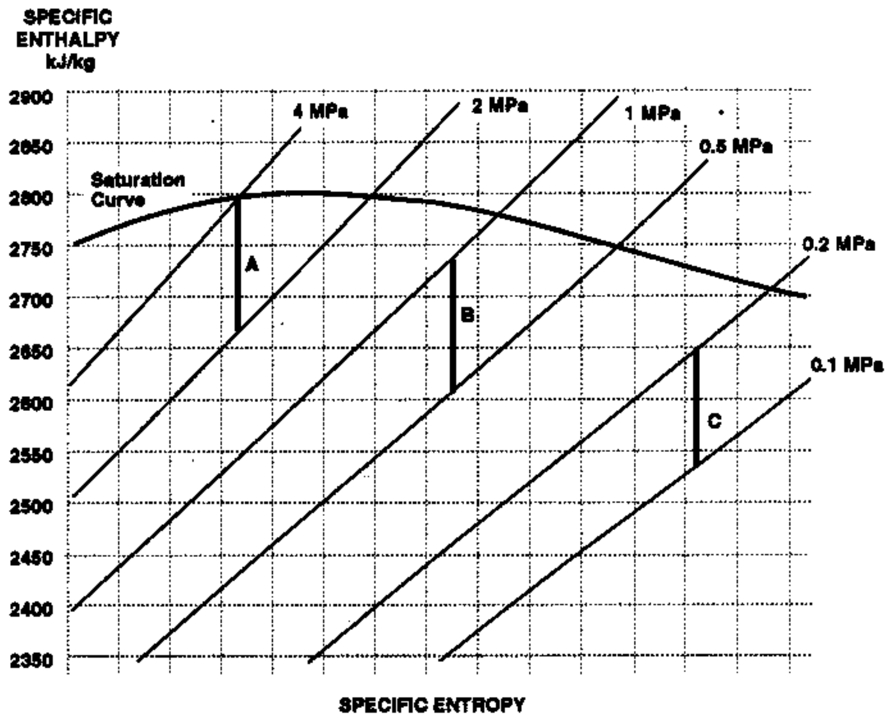

Fig. 1.2. Relation between inlet and outlet pressures and heat available in various turbine stages:

Case	P_{inl} [MPa]	P_{out} [MPa]	ΔP [MPa]	P_{inl}/P_{out}	Δh_{av} [kJ/kg]
A	4	2	2	2	130
B	1	0.5	0.5	2	130
C	0.2	0.1	0.1	2	120

Note that in all three cases, Δh_{av} is nearly constant (about 120-130 kJ/kg), the pressure ratio (p_{inl}/p_{out}) is the same, and yet the pressure drop varies substantially – from 2 MPa (in case A) to 0.1 MPa (in case C). The conclusion we can draw is that the available heat remains reasonably constant as long as **the pressure ratio** does not change. Note that this statement involves the pressure ratio, and **not the pressure drop**, across the stage.

If you now refer back to Fig. 1.1, you will recall that the interstage pressures are proportional to turbine load. Therefore, the pressure ratio in any one but the last stage **stays constant when turbine load varies**. Only in the last stage, the pressure ratio changes because the outlet pressure (approximately equal to condenser pressure) stays nearly constant, whereas the inlet pressure drops with decreasing load.

This has a profound effect on the performance of various stages. Since **all but the last stages operate at a constant pressure ratio**, their available heat (per kilogram of steam) does not change. Hence, the flow pattern in these stages does not deteriorate. Needless to say, **their efficiency remains approximately constant***.

* We neglect here other factors, eg. moisture in steam, that can be affected by turbine load. However, they are of secondary importance in comparison with the pressure ratio.

But **in the last stage**, the pressure ratio, and hence the available heat, decrease when turbine load is reduced. Gradually, **the flow pattern deteriorates** as shown in Fig. 1.3. Note that a positive flow (ie. towards the exhaust) is preserved only in the outer region of the blades, while an intensive recirculation occurs in the remaining region. Why? At light/no load, the turbine steam flow is greatly reduced. In the last stage, whose outlet pressure (and hence, steam density) does not change much with turbine load, this leads to a significant **reduction in the volumetric flow**. For this flow, the blades are just too long. Due to the action of centrifugal forces, the positive flow occupies only the outer region of the blades. The steam in the remaining region is churned by the blades and recirculates as shown in the sketch below.

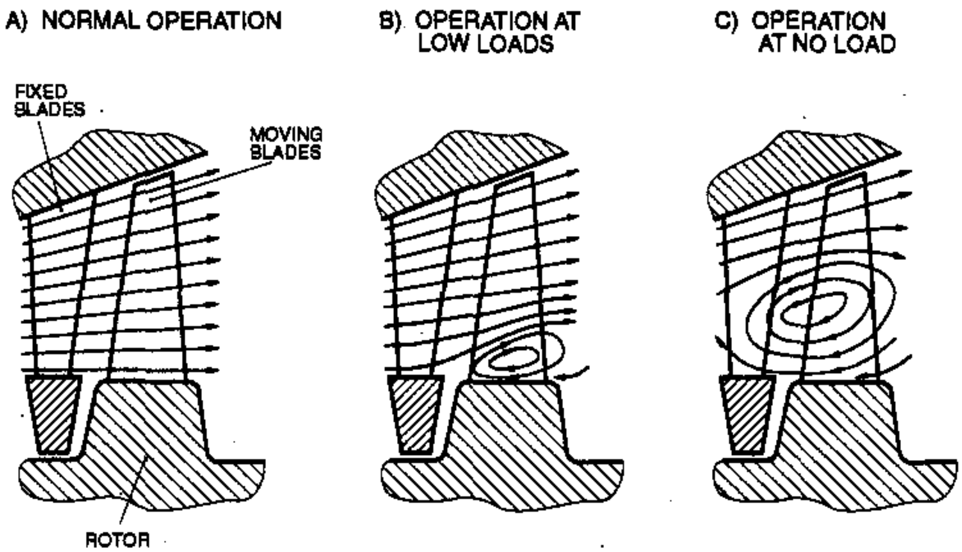

Fig. 1.3. Simplified flow pattern in the last stage at various turbine loads.

At a certain load*, deterioration of the flow pattern becomes so large that the stage MW output and efficiency drop to zero. The stage is said to be **choked with the steam flow**. The choking causes the stage inlet pressure to cease dropping proportionally with turbine load. Note that this affects the pressure ratio in the second last stage. So, when turbine load is reduced further, the flow pattern in that stage also deteriorates gradually. As a result, the stage output and efficiency decrease, as it has already happened in the last stage. At the same time, flow conditions in the last stage get even worse, causing it to consume, through windage losses, some of the power produced by the other stages.

* In most stations, this happens at a turbine load of about 6-7% FP.

With further reductions in turbine load, **these effects propagate upstream through the turbine**. At no load and normal speed condition (eg. prior to synchronization), a few of the last stages of the turbine are driven by the remaining stages and dissipate mechanical power as frictional heat.

NOTES & REFERENCES

It is worth emphasizing that a poor flow pattern in the last few stages creates **more operational concerns** than just reduced turbine efficiency. First, large windage losses produce so much heat that a special cooling system is required to prevent **overheating of the LP turbine exhaust**. Second, the flow becomes so turbulent that it can induce **excessive blade vibration**. These important operational problems are discussed in detail in other modules of this course; from the above description of the last stage operation, you can understand why they can occur.

Note that **poor condenser vacuum aggravates these problems** because it reduces further the already low pressure ratio in the last stage(s), thereby contributing to deterioration of the flow pattern.

SUMMARY OF THE KEY CONCEPTS

- Except for very light loads, turbine interstage pressures change proportionally with the turbine load. The same applies to the turbine inlet pressure in the turbines where the governor valves operate in unison. The exhaust pressure is assumed to stay constant.
- Stage performance depends on the steam flow pattern. The latter is greatly affected by the amount of available heat.
- The amount of heat available to a turbine stage depends on the pressure ratio across the stage.
- When turbine load is reduced, the pressure ratio in any one but the last stage stays reasonably constant. Thus, the flow pattern remains unchanged, and the stages operate as efficiently as at full power.
- In the last stage, the pressure ratio decreases with reduced turbine load. As less heat is available, the steam velocity decreases. Consequently, the stage output drops.
- At a certain load, the last stage starts drawing power from the other stages. The flow pattern in this stage is so deteriorated that the stage is choked with the flow. Therefore, the inlet pressure ceases to decrease proportionally with the load. This reduces the pressure ratio in the second last stage whose performance begins to deteriorate.
- These effects propagate gradually upstream through the turbine as its load is further reduced.

Pages 27-28 ⇔

You can work now on **assignment questions 1-5**.

NOTES & REFERENCES

MOISTURE IN TURBINE STEAM

The following topics are discussed in this section:

- The adverse consequences of wet turbine steam;
- Abnormal operating conditions that cause excessive wetness of turbine steam.

ADVERSE CONSEQUENCES

⇔ Obj. 1.2 a)

As you have already learned in the previous turbine courses, the presence of moisture in turbine steam has two serious adverse consequences:

1. **Reduced turbine efficiency** which increases the fuel costs as more fuel must be "burned" to maintain the output;
2. **Erosion of turbine components** which increases the maintenance costs and, in the worst case, can cause failure.

However, moisture in turbine steam also creates other problems such as:

3. **Accelerated corrosion of turbine components**;
4. ***Increased turbine overspeed potential***.

Each of these consequences is discussed below.

Loss of turbine efficiency

⇔ Obj. 1.2 b)

There are two **major reasons** why moisture in turbine steam decreases turbine efficiency:

1. **Water droplets disturb the steam flow, resulting in increased friction losses and hence, reduced efficiency.**

   Water droplets disturb the steam flow because they move slower and in different directions than the steam.

   The reason why water and steam move in different directions is that whenever the direction of flow is changed, **water droplets** in the steam **are centrifuged** (Fig. 1.4 on the next page) because their density is much higher than that of the steam.

NOTES & REFERENCES

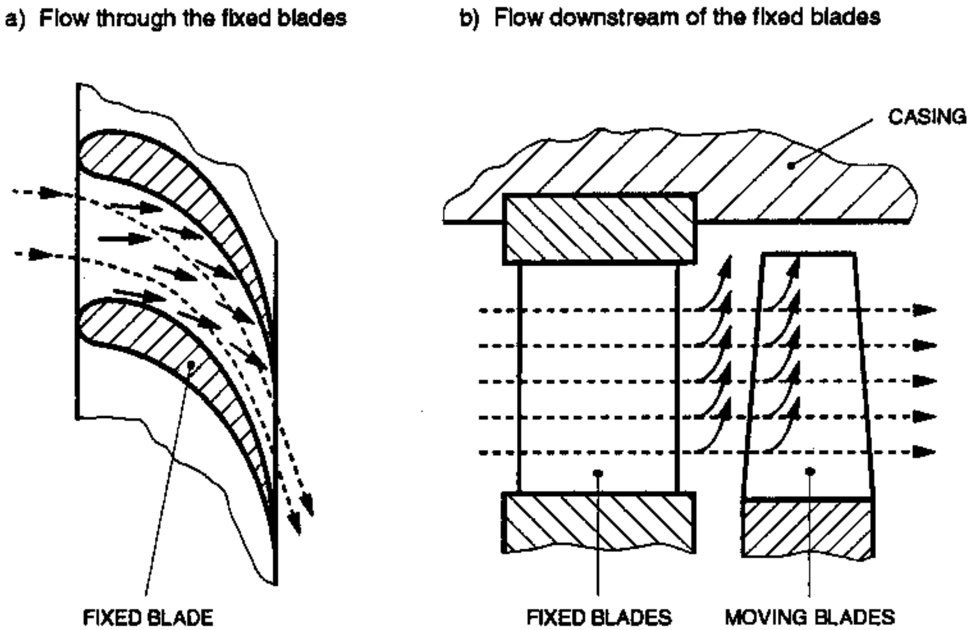

Fig. 1.4. Steam and water trajectories in a turbine stage:
----------- Steam ——— Water

The reason why water moves slower than steam through the turbine is that water, as opposed to steam, does not fill the channels between the blades. Thus, water is not accelerated directly by the turbine nozzles. Rather, **water droplets are driven by the steam** much the same way as snow flakes are blown by a strong wind.

The nature of this process is such that the driving force, that the steam exerts on a water droplet, would decrease to zero if the steam and water velocities equalized. Therefore, when steam accelerates in a nozzle, water droplets always fall behind. The velocity difference increases with the size of the droplet because it is more difficult for the steam to move it. Thus, the larger the water droplet is, the slower it moves.

2. **Water droplets collide with moving blades, thereby retarding their motion.**

   This is a direct consequence of the fact that water droplets move slower than the steam as described above. As a result, some droplets that enter moving blades move slower than the blades themselves. When the moving blades hit the droplets from the back, these collisions produce forces which retard the blade motion. As the driving torque developed by the steam is reduced **due to this retarding effect, the turbine MW output is decreased** as well.

These two effects combined reduce turbine stage efficiency by about 1% per each 1% of the average moisture content of steam.

NOTES & REFERENCES

Erosion

⇔ *Obj. 1.2 c)*

Wet steam causes three different **types** of erosion:

1. **Impact erosion – caused by collisions of droplets with the surface of a component.** In steam turbines, **the leading edge of moving blades** close to their tip is the most typical site of this type of erosion. Recall that this region of the blades experiences intensive bombardment by water droplets as explained above.

2. **Wire drawing erosion – caused by the cutting action of water which is forced to leak through a joint due to a large pressure difference across the joint.** Note that this erosion is a self-accelerating process – once a small groove has been cut, the leakage rate increases, cutting the joint even faster. This type of erosion is quite common in steam piping where it can quickly damage a leaking flange joint.

   In steam turbines, this erosion can happen, for instance, in **the horizontal joint between two halves of a diaphragm** (Fig. 1.5). During normal operation, steam leakage through such a joint is very unlikely. However, some improper operating practices can establish a leak path through the joint. For example, this can happen during turbine startup or power manoeuvres if the diaphragm is subjected to abnormally large thermal deformations due to an excessive rate of heating or cooling. Because steam flows mainly through the blades, the outer part of the diaphragm follows steam temperature changes faster than the inner part does. The resultant deformation of the diaphragm is shown, grossly exaggerated, in Fig. 1.5.

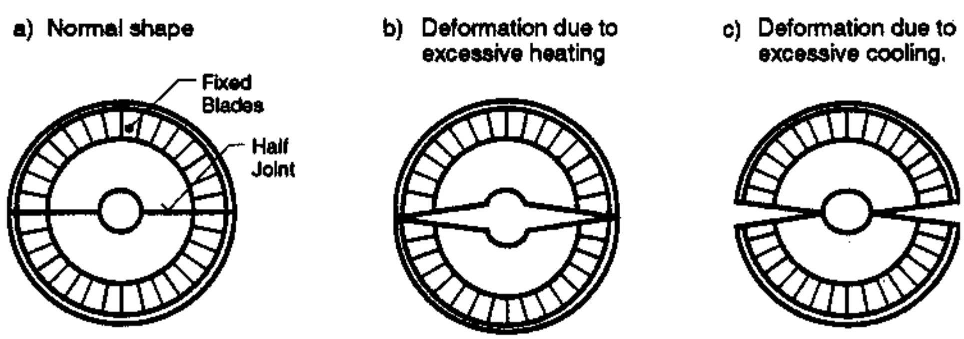

Fig. 1.5. Thermal deformations of a diaphragm.

3. **Washing erosion – caused by a cutting action of water moving very quickly along a surface.** This erosion is promoted when a water film is created on a surface and the film is dragged quickly by the steam. For example, this situation can occur in **steam pipelines at the HP turbine outlet** where steam is very wet which promotes formation of a water film, particularly in pipeline elbows. Inside the turbine, this type of erosion can damage **the concave surface of fixed blades** onto which water is centrifuged (Fig. 1.4 a) and quickly dragged by the steam whose velocity is very high.

Excessive erosion of turbine components increases maintenance costs and promotes equipment failure by weakening components and concentrating the local stress in the eroded areas. The latter is caused by surface imperfections produced by erosion. **Advanced erosion of the turbine blades also reduces the turbine efficiency** by increasing the blade surface roughness and spoiling the blade shape.

The rate of any erosion increases dramatically with increasing moisture content of the steam. Therefore improper operating practices or malfunction of the equipment used for moisture removal from the turbine steam can result in an unacceptable rate of erosion. The most likely causes of excessive wetness of steam are identified later on in this module.

Corrosion

Obj. 1.2 d) ⇔

Wet steam also promotes various corrosion mechanisms. The presence of **water** (which always contains dissolved oxygen and other impurities, eg. chlorides) in a steam turbine **sets up good conditions for general electrochemical corrosion** because it provides an electrolyte, without which electrochemical corrosion is impossible.

Much more dangerous, however, are other types of corrosion which attack locally and can form deep cracks. Among these, **stress corrosion cracking and corrosion fatigue*** are known to have caused many failures of turbine components such as blades, discs and rotors. Wet turbine steam promotes both these types of corrosion because **water can deposit impurities in highly stressed places** such as blade roots. This is particularly bad during cold startups due to large condensation of steam. When the turbine becomes hot later, **the condensate evaporates, leaving concentrated impurities on the surface** in hard-to-reach places where flowing steam cannot provide a washing effect. Unfortunately, these hard-to-reach places are often heavily stressed.

* Recall that stress corrosion cracking refers to a combination of a high constant tensile stress with a corrosive environment. Likewise, corrosion fatigue is a cyclic stress combined with a corrosive environment.

A combination of corrosion and erosion known as **erosion/corrosion** can cause damage faster than either of them acting independently. This is due to **erosion wearing away the protective layer** (eg. magnetite on carbon steel) and exposing more surface to the corrosive environment. **The corrosion products** that are formed **are usually less erosion-resistant** than the parent metal, thereby promoting further erosion. In other words, erosion helps corrosion in wearing away the metal and corrosion reciprocates in a similar way.

An understanding of the various corrosion mechanisms enables you to realize how **some incorrect operating practices can promote corrosion damage**. Poor chemistry control of boiler water and steam, and prolonged operation with excessively wet steam are some, to name a few.

Increased overspeed potential

⇔ ***Obj. 1.2 e)***

Finally, **wet steam increases turbine overspeed potential** when the turbine generator is suddenly disconnected from the grid. As you know, an automatic response to this upset is to cut off steam flow to the turbine in order to remove the driving torque. This action causes pressure inside the turbine to drop quickly because the turbine is directly connected to the condenser. As a result, **a portion of the moisture inside the turbine *flashes to steam which continues to drive the turbine***, *thereby increasing its overspeed.* The wetter the turbine steam is, the more water can flash to steam and hence the overspeed potential is increased.

SUMMARY OF THE KEY CONCEPTS

- Moisture in the turbine steam reduces turbine efficiency, erodes and corrodes turbine components, and increases the overspeed potential.
- Turbine efficiency is reduced by moisture in the steam due to its retarding effect on the moving blades and the disturbance of the steam flow by water droplets.
- Three types of erosion – impact, washing and wire drawing – can damage various turbine components.
- Water in steam supports various corrosion mechanisms because it acts as an electrolyte, deposits impurities on the surface of heavily stressed components, and erodes away the protective layer.
- Wet steam increases the turbine overspeed potential as water flashes to steam upon a rapid pressure drop inside the turbine caused by cutting off the steam supply.

NOTES & REFERENCES

Obj. 1.3 ⇔

Operational causes of excessive wetness of turbine steam

During normal operation the average moisture content of steam in any turbine stage is kept within an acceptable range, ie. below about 10%. Some **operating conditions may**, however, **result in excessive wetness of steam in some or all turbine stages**. Listed below are a few examples:

1. **Abnormally high moisture content of steam at the HP turbine inlet.**

   This can be caused by a few reasons. For one thing, the boiler may supply steam much wetter than expected. The next module covers this operational problem in detail. Poor operation of the main steam pipelines between the boiler and the HP turbine can be another reason. It can be caused by malfunctioning steam traps and/or drain valves, or excessive steam condensation in the pipelines. More information on this topic is given in module 234-3.

2. **Loss of reheating.**

   Partial or total valving out of the reheaters causes steam wetness in the LP turbine to increase. While this aggravates all the adverse consequences of moisture in turbine steam, erosion is affected most*. This is the main reason why full load operation without reheating can be tolerated only over a very short period of time and should be avoided altogether to preserve the turbine life. Module 234-4 covers this topic in more detail.

* A total loss of reheat has been estimated to accelerate the erosion rate about tenfold!

3. **Malfunctioning moisture separator(s) and/or reheater(s).**

   Such a malfunction can be caused, for example, by mechanical damage to the chevron plates in a moisture separator, reheater or moisture separator drains level control problems or reheater tube fouling. No matter what the actual cause of the malfunction is, it results in an increased wetness of the steam in the whole LP turbine.

4. **Significant reduction in extraction steam flow.**

   A large loss of feedheaters (eg. one bank of LP feedheaters valved out) reduces the total flow of extraction steam. Since extraction steam contributes to moisture removal from the turbine, this results in somewhat increased wetness of turbine steam.

5. **Clogged turbine drains.**

   This results in increased moisture content of steam in the downstream stages. In addition to the adverse consequences described earlier in this module, clogged turbine drains can result in accumulation of water at the casing bottom. Since the accumulated water impedes heat flow from steam to the casing, the latter gets somewhat cooler, and therefore shrinks accordingly. The resultant humping deformation of the whole casing can be large enough to cause rubbing and increased turbine vibration.

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- Excessive wetness of turbine steam can be caused by a loss or malfunction of a reheater, poor performance of moisture separator(s) or plugged turbine drains. A significant reduction in the extraction steam flow or abnormally high wetness of the HP turbine inlet steam can be other reasons.

You can now work on **assignment questions 6-10.**

⇔ *Pages 28-29*

AXIAL THRUST

The previous turbine courses described how axial thrust on the turbine generator is created and what methods are used to carry or minimize it during normal operation. This course discusses an abnormally high thrust: you will learn how it can damage the turbine, what may cause it and how to recognize that it is taking place.

Operating concerns caused by excessive axial thrust

⇔ *Obj. 1.4 a)*

You will recall that the axial thrust is carried by a thrust bearing which fixes the rotor in the axial direction with respect to the casing and hence prevents rubbing of turbine internals. An excessive thrust causes therefore two major adverse consequences/operating concerns:

1. It **accelerates wear** of the thrust bearing and **may** lead to its **damage.**

   If the thrust is several times normal, the bearing may get damaged immediately.

2. **If** damage to the thrust bearing is substantial, the **rotor can move** enough in the axial direction to cause **axial rubbing** that **can damage turbine internals** (seals, blades, discs and diaphragms).

Operational causes of excessive axial thrust

⇔ *Obj. 1.4 b)*

Excessive axial thrust can be caused by:

1. **Axial rubbing.**

   This can be due to excessive difference between the axial thermal expansions of the casing and rotor*, damaged or loosened turbine generator internals, or incorrect assembly of the machine. The axial forces acting between the rubbing parts exert an extra load on the thrust bearing.

   * This problem is discussed in module 234-11.

2. **Water induction to the turbine***.

   Slugs of water can block blade passages, resulting in an abnormal pressure profile in the turbine. This can generate a load on the thrust bearing many times in excess of its normal value.

   * More information on water induction is given in module 234-13.

NOTES & REFERENCES

3. **Change in the steam flow distribution through the turbine due to:**

   a) **Change in the extraction steam flow distribution.**

   This can be caused by removing many feedheaters from service, damage to extraction steam piping, or malfunction of a check valve in the piping. Note that the extraction steam lines are not perfectly symmetrical with respect to the two halves of a double flow turbine. This makes the steam flow through the turbine asymmetrical because the resistances of each half of the turbine to the steam flow are not the same*. Consequently, a change in the extraction steam demand is not distributed evenly and can actually enhance the asymmetry of the main steam flow and pressure distribution in the turbine. As a result, an extra thrust can be generated.

   * You may remember that this is done on purpose to determine the direction and magnitude of the axial thrust produced during normal operation.

   b) **Excessive deposits on turbine blades, their advanced erosion or some other damage.**

   Even in double flow turbines, any of the above can produce an extra thrust because the blading in the two halves of the turbine may be affected asymmetrically.

Obj. 1.4 c) ⇔

Indications of excessive axial thrust

How can we know that the axial thrust is excessive? Two most reliable indications of this potentially dangerous situation are:

1. **Abnormal shaft axial position.**

   As you know, the turbine generator rotor is fixed in the axial direction at **the thrust bearing.** This bearing, as everything else, is not infinitely rigid. Therefore, it **deflects under the thrust**. The larger the thrust, the larger the deflection. As a result, the shaft axial position changes accordingly, albeit very little*. Hence, monitoring of the shaft axial position allows us to check if the thrust acting upon the bearing is excessive.

   * Displacements are in the order of a few tenths of millimeter, at the most.

2. **Thrust bearing metal temperature abnormally high.**

   More frictional heat is produced in the bearing when it is loaded with increased axial thrust. Therefore, an excessive axial thrust can raise thrust bearing metal temperature abnormally high. Though the bearing oil outlet temperature can also be affected, operational experience shows that the bearing metal temperature is more sensitive to the axial thrust.

   However, a high bearing metal temperature indication **may also be caused by a few other reasons**, such as:

   a) Inadequate oil supply to the bearing (eg. oil too hot or in insufficient quantity to provide adequate cooling and lubrication);

   b) Advanced deterioration of the bearing itself, resulting in increased friction and impaired lubrication;

NOTES & REFERENCES

c) Faulty temperature instrumentation.

Therefore some investigation (eg. extra checks in the lubricating oil system) may be necessary to pinpoint the actual cause of this indication. **If it is,** however, **concurrent with an abnormal shaft axial position, an excessive axial thrust is almost certainly the cause of trouble.**

Both these parameters are continuously monitored. Typically, the monitoring is performed by more than one system, because these parameters are so essential to turbine safety. If a limit has been reached or exceeded, the turbine may have to be unloaded (to lower the pressure distribution in the turbine, thereby reducing the thrust) or tripped, or further loading during a startup may have to be postponed. Which action should be taken is clarified in the appropriate operating manual. Details in this matter will be covered in the station specific phase of the authorization training.

SUMMARY OF THE KEY CONCEPTS

- Excessive axial thrust results in accelerated wear of the thrust bearing. It can also severely damage the turbine – first, by wrecking its thrust bearing, and then by axial rubbing of turbine internals such as seals.
- Possible causes of excessive axial thrust include axial rubbing (eg. due to excessive axial differential expansion), water induction to the turbine, and a change in the steam flow distribution through the turbine (eg. due to taking many feedheaters out of service).
- An excessive axial thrust is indicated by an abnormal shaft axial position and high thrust bearing metal temperature.

You can now work on **assignment questions 11-14.**

⇔ *Pages 30-31*

TURBINE GLAND SEAL OPERATION

In the previous turbine courses, you learned about the functions and principles of operation of various turbine seals. The description given there was limited to normal turbine operation at full load. In this module, seal operation at partial loads and major upsets in seal operation will be discussed.

Operation of an LP turbine gland seal at partial loads

⇔ *Obj. 1.5*

Let us first recall the principle of operation of a **typical gland seal of an LP turbine.** The major task of this seal is to prevent air ingress into the LP turbine which operates under high vacuum. This is achieved by supply of sealing steam at low pressure (a few kPa(g)) to the seal at port A as shown in Fig. 1.6 on the next page.

NOTES & REFERENCES

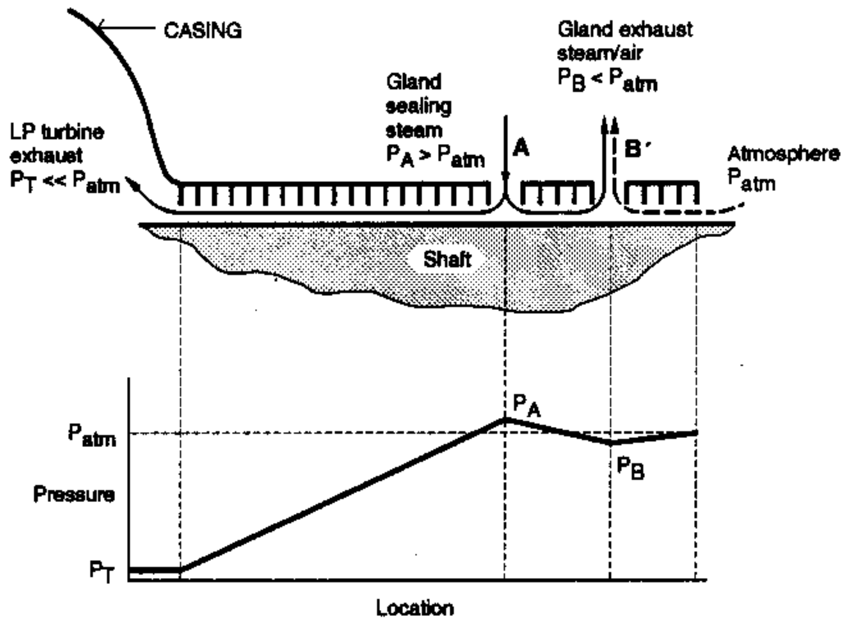

Fig. 1.6. Normal operation of a LP turbine gland seal: ——— Steam; – – – Air; A and B = External connections to the gland sealing steam system.

To prevent egress of this steam into the turbine hall, port B of the seal is connected to a gland exhaust condenser which operates slightly below atmospheric pressure. The resultant steam and air flow paths and a simplified pressure distribution are shown in Fig. 1.6. Note that **turbine load does not affect operation of this seal because high vacuum is maintained at the LP turbine exhaust at all power levels.**

Operation of an HP turbine gland seal at partial loads

This is more complicated because:

a) **The HP turbine exhaust pressure varies**, depending on the turbine operating condition as outlined below and;

b) While LP turbine gland seals are very similar in all stations, this unfortunately does not hold true for HP turbine gland seals. **Many various designs** of these seals are used in CANDU stations, as their turbines have been built by different manufacturers.

At high and medium loads, the HP turbine exhaust pressure is well above atmospheric so that air ingress into the turbine is of no concern. Instead, high pressure **steam egress** into the turbine hall must be prevented. But at very light loads, during turbine startups, as well as those rundowns and shutdowns when condenser vacuum is still maintained, the HP turbine exhaust pressure drops below atmospheric and the seal must then prevent **air ingress.**

NOTES & REFERENCES

These problems have been solved by turbine manufacturers in a few different ways. The seal shown in Fig. 1.7. is fairly simple as it has only two external connections. When the turbine operates at high and medium loads, the seal is self-sealing (ie. it does not need any sealing steam), and its leak-off (at connection A) is typically utilized as sealing steam in LP turbine gland seals. Whenever turbine load drops below a certain level, this seal requires sealing steam to prevent air ingress. The pressure distribution and steam/air flow paths in the seal then become similar to those in the LP turbine glands (compare Fig. 1.6 and 1.7 b).

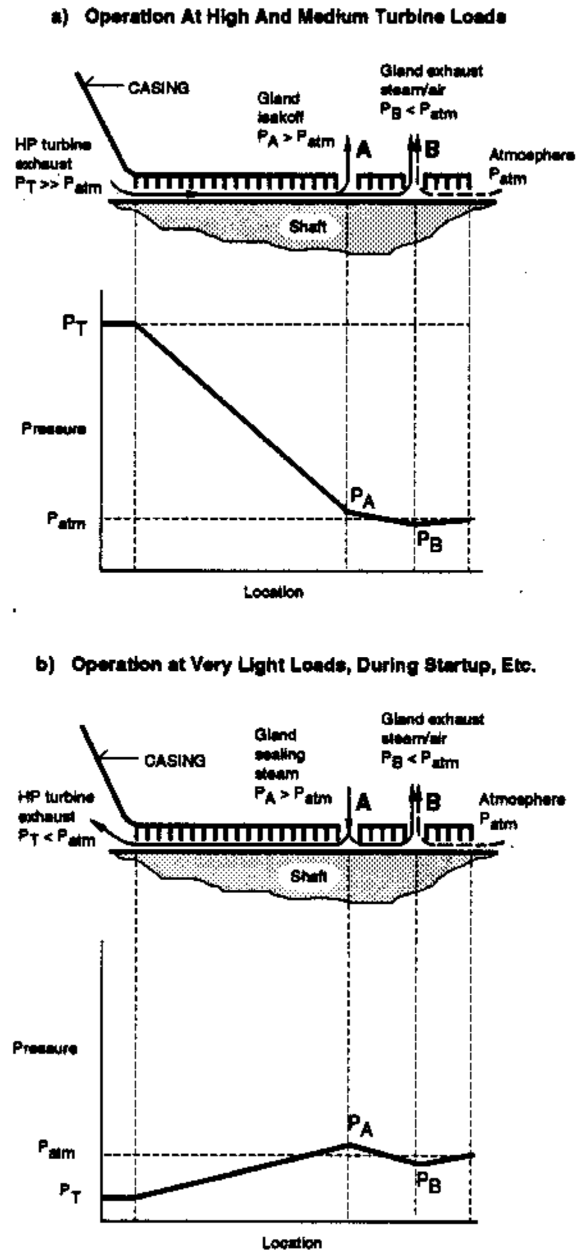

Fig. 1.7. Normal operation of a HP turbine gland seal:
—— Steam; ----- Air; A and B = External connection to the gland steam sealing system.

NOTES & REFERENCES

Other designs of the HP turbine gland seal may have more external connections, their leakoff may be utilized in another way (eg. for feedheating) and some of them may require sealing steam all the time (ie. they are never self-sealing)*. Since any attempt to cover all these variations would be impractical and confusing, this module describes only one type of an HP turbine gland seal. As it may not be exactly the type used in your station, the station specific training will supplement the required information. For now, just remember that the information on the HP turbine gland seal that is presented in this module is very general and may not be fully applicable to your station. Nevertheless, you have learned that, **at least in some stations, the HP turbine gland seals are greatly affected by the turbine operating condition** – they may be self-sealing at high and medium loads, but require sealing steam when the HP turbine exhaust pressure drops below atmospheric.

* The HP turbine glands shown in Fig. 4.6 at the end of module 234-4 are an example of such seals.

Obj. 1.6 ⇔

Rubbing in turbine seals

All turbine seals, both external and internal, are designed with the clearances between the rotating and the stationary parts as small as possible. While this minimizes steam leakage, and hence keeps the turbine efficiency high, it also promotes rubbing.

Rubbing is the major operational problem with all turbine seals because their small clearances can be closed up relatively easily. This usually happens due to high vibration or excessive thermal or mechanical deformations of the turbine casing and/or rotor.

Seal rubbing is particularly likely during initial startups of the turbine. This is because some manufacturers make the radial clearances within turbine seals slightly too tight in order to avoid undue leakage losses caused by excessive clearances. Thus, during a few initial startups, some mild rubbing is expected to increase clearances to their proper values. Needless to say, these startups must be carried out extremely carefully.

All modern turbine seals are designed to accommodate **light rubbing without any damage to the turbine**. For example, the stationary parts of gland seals and diaphragm seals are flexibly supported and they are made of soft materials (eg. lead bronze) to prevent/minimize damage to the shaft. Similarly, the tips of free-standing (ie. shroudless) moving blades are thinned so that rubbing can wear them out without bending or breaking the blades themselves. While these measures are effective against light rubbing, they cannot protect the turbine in case of **more intensive rubbing**.

Obj. 1.7 a) ⇔

Listed below, in the order of severity, are the **adverse consequences/ operating concerns** caused by such rubbing:

1. **Damage to the rubbing seal(s).**

   Damage to turbine seals results in increased clearances between the fixed and moving components. Therefore, turbine efficiency is permanently reduced due to increased steam leakage through the damaged seal(s).

NOTES & REFERENCES

This adverse consequence applies to both internal and external seals. But severe damage to an external seal has additional consequences, which are the same as those caused by insufficient sealing steam pressure (described in the following section).

2. **High turbine rotor vibration** due to:

   a) Direct effect of the forces generated by the rubbing and;

   b) Thermal bending of the rotor.

      Here is how it happens. When rubbing occurs in a turbine seal, only a small arc of the shaft surface is, at any given time, in contact with the stationary part of the seal. Therefore, frictional heat at the site of rubbing does not heat the shaft evenly. Instead, it produces a **hot spot** on the shaft surface. The resultant thermal expansion of the shaft causes it to bow. This increases its unbalance and hence, vibration.

   High rotor vibration can force a **turbine trip** and result in **damage*** to the machine.

* Turbine generator damage due to high vibration is described in module 234-14.

3. **Severe damage to other turbine internals.**

   For example, deep grooves can be cut on the shaft surface by the stationary parts of the rubbing seals. Or, some blades can get bent or even broken off if their seals are involved in the rubbing. Also, localized heating of the shaft may produce thermal stresses so large that the shaft can bow permanently. In any case, damage would be accompanied by very high vibration.

In the extreme case, a long outage may be necessary for costly repairs to the turbine.

Abnormal pressure of gland sealing steam

⇔ ***Obj. 1.7 b)***

Trouble-free operation of any turbine gland seal requires proper adjustment of its **sealing steam pressure**. When this pressure **increases above its normal value**, the sealing steam flow through the seal increases and pressure at port B rises as more steam flows out of the seal and into the gland exhaust condenser. Eventually, pressure at port B can rise above atmospheric, **causing hot steam* to blow out of the seal.** This is shown in Fig. 1.8 on the next page.

* At temperature of about 140-150°C.

NOTES & REFERENCES

In the drawing below, part a) illustrates an HP turbine gland seal whose leakoff is utilized as sealing steam in LP turbine gland seals. Part b) of this figure shows an LP or HP turbine gland seal operating against turbine exhaust pressure below atmospheric.

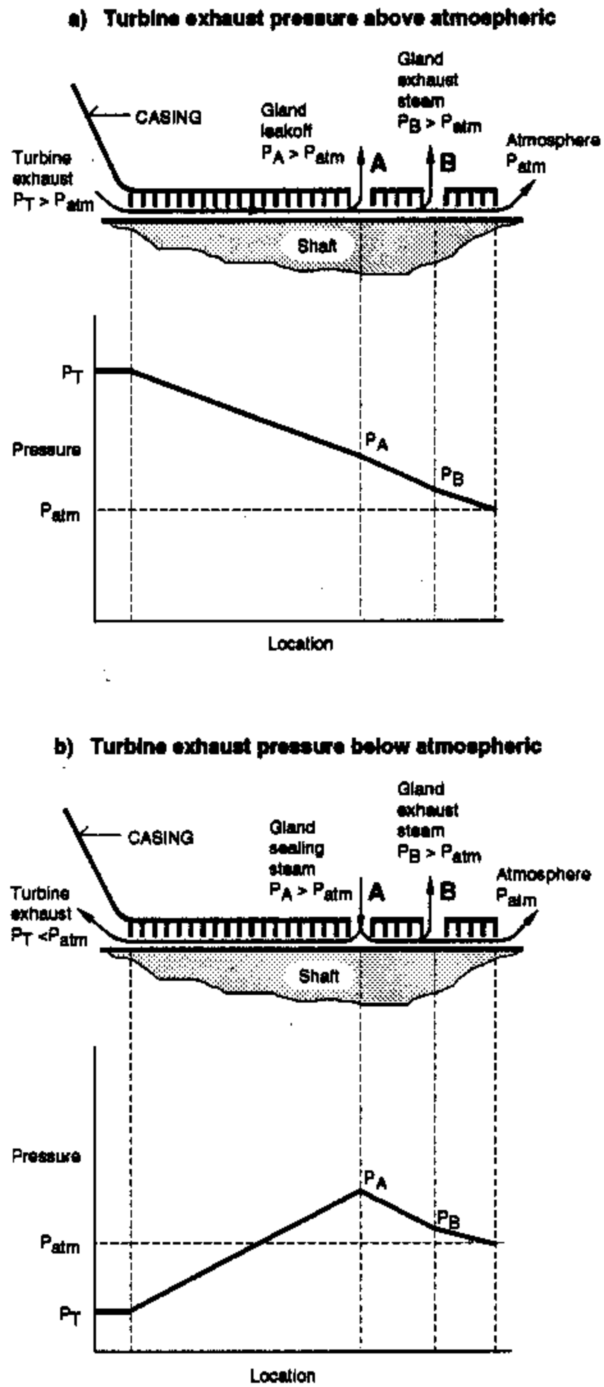

Fig. 1.8. Operation of a turbine gland seal with excessive pressure of its sealing steam: A and B = External connections to the gland steam sealing system.

In either case, the steam blowing out of the seal can **overheat the adjacent bearing** (if leakage is large enough). **Contamination of oil in the bearing with water** can also result because the leaking steam can penetrate the bearing seal and condense inside. Both these problems are covered in more detail in other modules of this course. Note that the axial distance between turbine gland seals and bearings is very small (to reduce the total length of the turbine generator). Therefore, it is not difficult for leaking gland steam to reach the nearest bearing.

Of course, any steam leak represents a safety hazard and causes increased consumption of makeup water. In this case, however, the safety hazard is nearly nonexistent because during turbine operation it is very unlikely that someone will be close to the leaking seal. Likewise, the cost of increased makeup is small in comparison with the cost of a bearing repair which would require a turbine shutdown.

⇔ Obj. 1.7 c)

When the sealing steam pressure at the inlet to a gland seal is too low, air can leak into the turbine through the malfunctioning seal. This problem can occur in any LP turbine gland seal at any power level or in an HP turbine gland seal whenever the HP turbine exhaust pressure is below atmospheric.

The actual steam and air flow paths inside the malfunctioning seal depend on its design which, in the case of the HP turbine gland seal, varies from one station to another. Along with this, the type of the gland sealing steam supply failure (ie. total or partial loss to all the seals or only to one seal) also affects the flow paths. To cover all these cases would be impractical and confusing. Therefore for simplicity, Fig. 1.9 on the next page illustrates only one case: an LP turbine gland seal malfunctioning due to a total loss of gland sealing steam to all the seals.

NOTES & REFERENCES

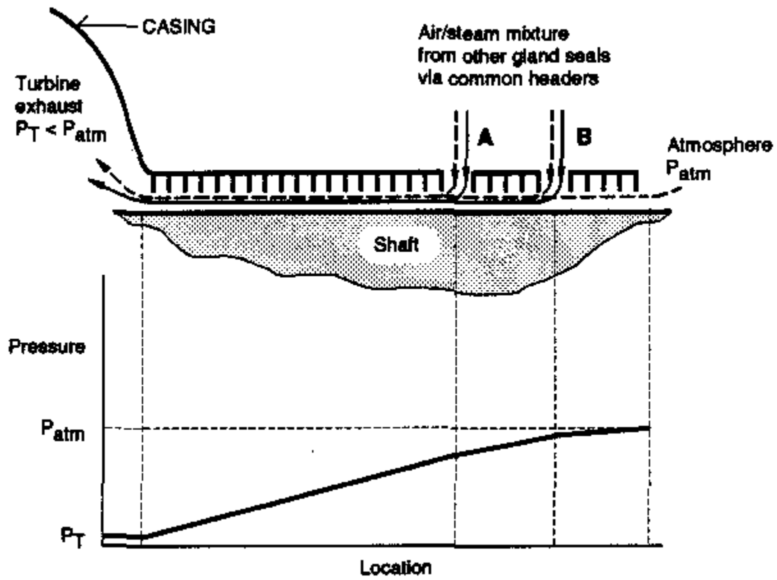

Fig. 1.9. Operation of a LP turbine gland seal with insufficient pressure or loss of its sealing steam:
—— Steam; - - - Air; A and B = External connections to the gland steam sealing system.

Note in Fig. 1.9 that the sucking action of vacuum inside the turbine can lower pressures at ports A and B so much that the malfunctioning seal can actually draw an air/steam mixture from other seals via common headers in the gland sealing steam system that connect all the glands together.

Air inleakage that results from a loss of gland sealing steam pressure to one or more glands causes the following **adverse consequences/ operating concerns**:

1. **Increased air concentration in the condenser**, resulting in:

   a) **Reduced condenser vacuum** with all its adverse consequences as outlined in module 234-5;

   If many seals are leaking and no corrective action is taken, condenser pressure may quickly (within several minutes) rise enough to cause automatic **turbine unloading or even trip,** both representing a costly loss of production.

   b) **Increased concentration of dissolved oxygen in the condensate.**

   If the gland malfunction does not force a turbine trip and **operation is continued, accelerated corrosion** in the condenser and the condensate system is our major concern. The boiler feedwater and

NOTES & REFERENCES

steam systems, as well as the boiler and the turbine, are also affected if the hydrazine injection rate is not increased properly.

To minimize corrosion damage, the allowable duration of operation is limited and proper actions must be taken when certain limits on the oxygen content are reached. **In the extreme case, the unit must be shut down.** Details on those limits and actions are specified in the appropriate operating manual and left for the station specific training.

2. **Quenching of hot parts of the malfunctioning seal(s) by cool in-leaking air.** The quenching can produce thermal stresses large enough to cause **cracking of the seal segments and/or increased turbine vibration.** Also, **abnormal axial differential expansion** can occur*.
3. A total loss of sealing steam to a turbine gland can cause condenser vacuum to **suck in lube oil** from the adjacent bearing. The resultant **contamination of boiler feedwater** can cause **foaming and asphalt-like deposits in the boilers.**

* Axial differential expansion is explained in module 234-11.

SUMMARY OF THE KEY CONCEPTS

- Operation of LP turbine gland seals is not affected by turbine load.
- In many stations, the HP turbine gland seals are self-sealing when the HP turbine exhaust pressure is sufficiently above atmospheric but they require sealing steam when this condition is not met. In other stations, these seals require sealing steam all the time.
- Rubbing is the major operational concern with all turbine seals because of the tight clearances used.
- While light rubbing can be accommodated, more intensive rubbing can damage seals and other turbine internals as well as increase turbine vibrations. A forced outage and costly repairs may result.
- Excessive gland sealing steam pressure results in steam egress that can overheat the bearing adjacent to the malfunctioning seal. Contamination of the oil in the bearing with condensing steam is also possible.
- Insufficient pressure of gland sealing steam causes air ingress into the turbine, resulting in reduced condenser vacuum and increased dissolved oxygen content in the condensate. In the extreme case, turbine unloading and trip on low condenser vacuum can occur, or the increased dissolved oxygen content in the condensate may force a unit shutdown. Second, quenching of the malfunctioning seal by in-leaking air can damage the seal, increase turbine vibration and produce abnormal axial differential expansion. Third, bearing oil may get sucked into the turbine

NOTES & REFERENCES

and contaminate boiler feedwater which may lead to foaming and asphalt-like deposits in the boilers.

Pages31-32 ⇔

You can now work on **assignment questions 15-19.**

NOTES & REFERENCES

ASSIGNMENT

1. Except for operation at very light loads, all turbine interstage pressures change with turbine load as follows: ______________________

2. a) For efficient operation, the flow pattern must match ___________

   ____

   b) The flow pattern in a turbine stage changes with the amount of heat available per kg of steam because __________________

   ____

   ____

   c) The amount of the available heat stays approximately constant as long as the steam pressure (drop / ratio) across the stage does not change.

3. When turbine load is reduced, the amount of the heat available to the turbine, per kilogram of steam, (decreases / increases). The effect (is distributed evenly between all the stages / occurs only in the first few stages / occurs only in the last few stages).

4. a) At light turbine loads, the flow pattern in the (first / last) stage is significantly deteriorated. The steam in the stage moves too (fast / slowly) to be able to drive the moving blades. Large _________ losses occur when the steam is churned by the blades. This may eventually lead to the stage being driven by the other stages of the turbine or the generator. (False / true)

   b) The flow deterioration discussed in point a) above propagates (downstream / upstream) the turbine when its load is sufficiently reduced. This happens as follows:

   ____

   ____

   ____

   ____

   ____

   ____

   ____

   ____

   ____

NOTES & REFERENCES

c) The effect of turbine load on the performance of the remaining turbine stages is negligible because ____________________

____

____

____

5. Prolonged operation at very light or no load conditions promotes the following operational problems:

a) ____________________

b) ____________________

6. a) Moisture in turbine steam disturbs the steam flow because

____

____

b) Water droplets and steam move in (different / the same) directions because ____________________

____

____

c) Water droplets move (faster / slower) than steam because

____

____

____

____

____

7. a) Impact erosion is caused by ____________________

____

Example of a typical component that may be damaged by impact erosion: ____________________

b) Washing erosion is caused by ____________________

____

Example of a typical component that may be damaged by washing erosion: ____________________

NOTES & REFERENCES

c) Wire drawing erosion is caused by ______________________

____

____

Example of a typical component that may be damaged by wire drawing erosion: ______________________

8. Wet steam promotes:

a) General electrochemical corrosion because ______________

____

____

b) Stress corrosion cracking and corrosion fatigue because _____

____

____

____

____

____

c) Erosion-corrosion because ______________________

____

____

____

9. Wet steam increases turbine overspeed potential because _________

____

____

____

____

10. Excessive wetness of turbine steam can be caused by the following operating conditions:

a) ____

b) ____

c) ____

d) ____

e) ____

NOTES & REFERENCES

11. An excessive axial thrust can have the following adverse consequences:

    a) ____

    ____

    b) ____

    ____

12. In double flow turbines used in CANDU stations, the steam flow and pressure distributions in both halves of the turbine (are / are not) identical.

13. a) An excessive axial thrust can be caused by:

    i) ______________________________________

    ii) ______________________________________

    iii) ______________________________________

    b) A change in the steam flow distribution through the turbine can be caused by:

    i) ______________________________________

    ii) ______________________________________

    c) When the steam flow distribution through the turbine is changed, an increased axial thrust on the rotor can result because

    ____

    ____

    ____

    ____

14. a) An excessive axial thrust is indicated by:

    i) ______________________________________

    ii) ______________________________________

    b) An excessive axial thrust results in an abnormal shaft axial position because ______________________________

    ____

    ____

    c) High thrust bearing metal temperature can be caused not only by an excessive axial thrust, but also by ____________________

    ____

15. a) HP turbine gland seals are always self-sealing as long as some steam is admitted to the turbine. (False / true)

    b) Operation of LP turbine gland seals (does / does not) depend on turbine load.

16. The major operational concern with all turbine seals is ___________

    Its occurrence is promoted by the use of small ________________

    in turbine seals.

17. a) Rubbing in the turbine can have the following adverse consequences:

       i) ____

       ____

       ii) ____

       ____

       iii) ____

       ____

    b) Rubbing in a turbine seal can increase turbine rotor vibration due to:

       i) ____

       ____

       ii) ____

       ____

18. When the gland sealing steam pressure is too high, (air ingress / steam egress) occurs, possibly resulting in:

    a) ____

    b) ____

19. a) Insufficient gland sealing steam pressure causes air ingress into the condenser, resulting in:

       i) ____

       ____

       ii) ____

       ____

NOTES & REFERENCES

b) In addition, quenching of the hot seal by the leaking air can cause:

i) ______________________________

____

ii) ______________________________

____

iii) ______________________________

____

c) Also, a total loss of sealing steam to a turbine gland causes the following concern:

____

____

____

____

Before you move on to the next module, **check the objectives** to make sure that you have not overlooked any important issue.

Prepared by: J. Jung, ENTD

Revised by: J. Jung, ENTD

Revision date: April, 1994