STEAM TURBINE STEAM SYSTEM

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Contents

Summary

The steam system supplies steam from the boiler or reactor to the turbine. Since this is the main source of energy transport it is a critical component in the plant. Valves control the admission of steam to the turbine and the system has a number of other components, not really regarded as part of the steam system but which rely on steam for their operation. The steam system for a water cooled reactor includes a reheater which reheats the steam leaving the high pressure turbine using live steam directly from the reactor. Most systems include a deaerator for eliminating air from and preheating it prior to feeding it to the boilers. All systems have feedwater heaters which use steam bled from the turbine to preheat feedwater going to the boiler or reactor. The last component in the steam system is the condenser where exhaust steam from the turbine is finally condensed before being pumped back to the boiler or reactor.

The condenser is an important component in the system as it handles the heat rejected by the steam cycle. This ranges from about 50 percent (fossil fueled plant) to about 65 percent (nuclear fueled plant) of the boiler or reactor heat input. Variations in condenser performance also affect the operation and work output of the turbine so it is important to maintain its performance at the optimum level.

1. Main Steam System

1.1. General

The purpose of the main steam system is to convey steam from the steam generating unit or the nuclear reactor, where it is produced, to the steam turbine which it drives to produce electrical power. Naturally a large amount of energy is conveyed in the system which operates under high pressures and temperatures. Although the system is essentially a passive system consisting of a set of fixed pipes it is subject to transient flow conditions and must be appropriately designed.

A typical system carries steam at 16 to 17 MPa and 540°C though supercritical systems operate up to 25 MPa and the same temperature. This requires very robust pipes capable of operating at red hot temperatures. Steam systems for water cooled reactors on the other hand carry steam at a lower pressure and temperature of around 7 MPa and 300°C respectively. Although the conditions are not so severe, the specific volume and mass flow rate of the steam are both greater so the pipework has to be much larger.

1.2. Fossil Fuel Fired Units

In fossil fuel fired steam generating units, steam is generated at a high pressure and temperature. It is partly expanded in the high pressure cylinder of the turbine and then returned to the boiler at an intermediate pressure for reheating to the same temperature. It then goes to the intermediate and low pressure cylinders of the turbine to complete its expansion. Reheating is necessary to ensure that the steam, after completing its expansion in the turbine, is not too wet. Steam leaving the exhaust of the turbine should not contain more than about 10% moisture.

The flow of high pressure steam entering the turbine is controlled by *governor valves* and *stop valves*. The former control the flow to ensure that the appropriate amount of steam enters the turbine to meet the electrical load demand, while the latter can close rapidly in an emergency to shut off the steam supply to the turbine.

The flow of intermediate pressure reheat steam is controlled in a similar manner. Although the reheat governor and stop valves are downstream of the main steam valves, a considerable amount of steam remains within the high pressure turbine, the reheater tubing in the boiler and in the interconnecting pipework. Without reheat governor and stop valves this steam would, after a load reduction, enter and continue to drive the intermediate and low pressure turbines while it expands down to a new lower pressure. This effect is most severe with a total load reduction as would occur in the event of a fault and tripping of the turbine.

1.3. Nuclear Reactor Units

The same principles as above apply to nuclear reactor steam generating units. Gas cooled reactors produce steam at the same pressure and temperature as fossil fuel fired units so their steam systems are very similar. Water cooled reactors produce saturated steam at lower pressures so their steam systems are somewhat different. For the latter, the steam supplied to the high pressure turbine is actually at an intermediate pressure so the steam volume is greater and the governor and stop valves larger. There are usually multiple parallel pipes conveying the steam from the steam generator to the turbine and provision may also be made for steam isolating valves in the steam lines at the reactor containment boundary to seal off the reactor in the event of an accident.

Reheating is still required at the lower steam cycle conditions to ensure adequate steam quality at the turbine exhaust. With the larger steam volume to be handled it is not practical to return the steam to its source for reheating and reheating is done locally in independent *reheaters* using some high pressure steam. Reheating is preceded by the removal of excess moisture from the steam leaving the high pressure turbine. Reheating with high pressure steam limits the maximum temperature of the reheated steam but there is still sufficient superheat to ensure that the low pressure turbine exhaust steam wetness is not more than about 10% wet.

The *separators* may be separate from or integral with the reheaters. If separate, they usually operate using centrifuge principles where the steam is given a strong swirl to throw out the moisture. If integral, sudden changes in the direction of the steam cause the moisture to be trapped by chevron type plates. The reheater generally consist of finned tubes carrying high pressure steam which condenses fully to water inside the tubes, while transferring its heat to the lower pressure steam flowing on the outside.

As with fossil fuel fired plants, reheat governing and stop valves are provided at the inlet to the low pressure turbines to control the flow of steam, which is trapped in the high pressure turbine, separators and reheaters and connecting pipework, following a reduction in load. Provision is also made to protect the moisture separators and reheaters from excessive pressure by releasing steam through relief valves in the event of an excessive pressure transient.

1.4. Steam System Operation

Although the steam pipework is a fixed system with no moving parts it is subject to various transient conditions. It must also deliver steam safely to the turbine under all conditions.

One important aspect of the steam pipework is the operation of the valves. In the event of a fault on the turbine, generator or electrical system, the steam supply must be isolated very quickly, usually in the fraction of a second, so the stop valves must operate quickly and reliably.

Another aspect is the possibility of pipe vibration due to sudden changes in steam flow or flow disturbances due to bends and fittings. Steam pipes must be suspended on flexible supports to allow for small changes in length due to thermal expansion. This would permit vibration in the absence of proper restraints and dampers so the design of these is an important aspect of steam pipework. Thermal effects are not confined to thermal expansion. To withstand the high steam pressures the pipe walls have to be thick enough to ensure a safe working stress. When the pipe is heated from cold with hot steam, the inside wall temperature rises faster than the outside wall temperature. This causes the inside of the pipe to try to expand while restrained by the outside. The inside is thus subject to a compressive stress and the outside to a tensile stress (in the absence of a stress due to internal pressure). If subjected to internal pressure at the same time, parts of the pipe may be subjected to stresses greater than the permissible working stress. The result is deformation or damage to the pipe. This can be avoided by limiting the rate of heating of the pipe and all systems thus have provision for slow heating by admitting a small quantity of steam before subjecting the pipe to the full steam temperature and pressure.

During heating of the steam lines, considerable quantities of steam condense on the inside surfaces of the pipes and must be removed via drains at the low points of the system. The drains are open during warming of the pipework to ensure that collected water is properly drained away and closed during normal operation. If not properly drained, water could be entrained with the flowing steam and carried into the turbine where it could cause severe thermal shock or impact damage to the turbine blading.

1.5. Condenser Steam Discharge Valves

The condenser discharge valves are used to control boiler pressure by discharging surplus steam to the main condenser. Under certain circumstances, when the turbine is unavailable and it is desirable to maintain load on a nuclear reactor, to prevent poisoning out with Xenon buildup, substantial quantities of steam may have to be discharged for an extended period. Such steam enters the condenser space at high velocity and in a hot superheated condition. To avoid thermal damage to the condenser structure and tubes and to the condenser neck joint, cool condensate is sprayed into the steam to cool it to normal condenser temperatures. Provision must also be made to avoid flow induced vibration due to the high velocities which are generated. A typical location of the steam discharge headers is shown in Figure 3 and Figure 4.

Certain limits are imposed on the operation of the condenser steam discharge valves. Under particular circumstances the condenser steam discharge valves are prevented from opening and discharging steam. Circumstances leading to this are reduced condenser vacuum or high turbine load when the capability of the condenser of absorbing on additional thermal load is limited.

2. Reheating and Feedheating

2.1. Reheaters

Water cooled nuclear rectors generate steam under saturated conditions at intermediate pressures. Reheating is required to ensure an adequate quality at the turbine exhaust. Reheating of the partially expanded steam at about 0.5 MPa (CANDU) to 1.1 MPa (PWR) is achieved by using high pressure steam from the reactor at about 5 MPa (CANDU) to 5.5 MPa (PWR).

Since the partially expanded steam flow, after separation of excess moisture, and the high pressure steam flow are both saturated, the difference in temperature between the two steam flows of about 100°C ensures adequate transfer of heat from the reheating to the reheated steam.

This is accomplished in a tubed heat exchanger with the high pressure steam flowing inside the tubes and the partially expanded steam on the outside. Since the steam inside the tube condenses to form a flowing water film, reasonable heat transfer coefficients are obtained. On the outside the steam becomes superheated and hence remains gaseous so fins are employed on the tubes to enhance the heat transfer. Ultimately the reheated steam temperature is raised to within 20°C of the reheating steam temperature.

The flow of reheating steam is governed by the flow of reheated steam. As the reheated steam extracts heat from the reheating steam the latter condenses. The greater the flow of reheated steam and hence the rate of heat extraction, the greater the rate of condensation and hence the required flow of heating steam to take its place. The system is thus self regulating provided the heating steam is fully condensed in the tubes and that they do not become internally flooded. The condensate flow leaving the tubes must therefore be released in a controlled manner. It is either pumped back into the steam generator (CANDU) or cascaded into the highest pressure feedwater heater (PWR).

2.2. Deaerator

The *deaerator* is part of the feedwater heating system and receives extraction steam from the turbine. The condensate to be heated and the extraction steam are intimately mixed in the deaerator by a system of spray nozzles and cascading trays between which the steam percolates as shown in Figure 1. The condensate is heated to saturated conditions and the steam condensed in the process. Any dissolved gases in the condensate are released in this process and removed from the deaerator by venting to the atmosphere or to the main condenser. This ensures removal of oxygen from the system particularly during startup of the turbine and minimizes the risk of corrosion within the rest of the system.

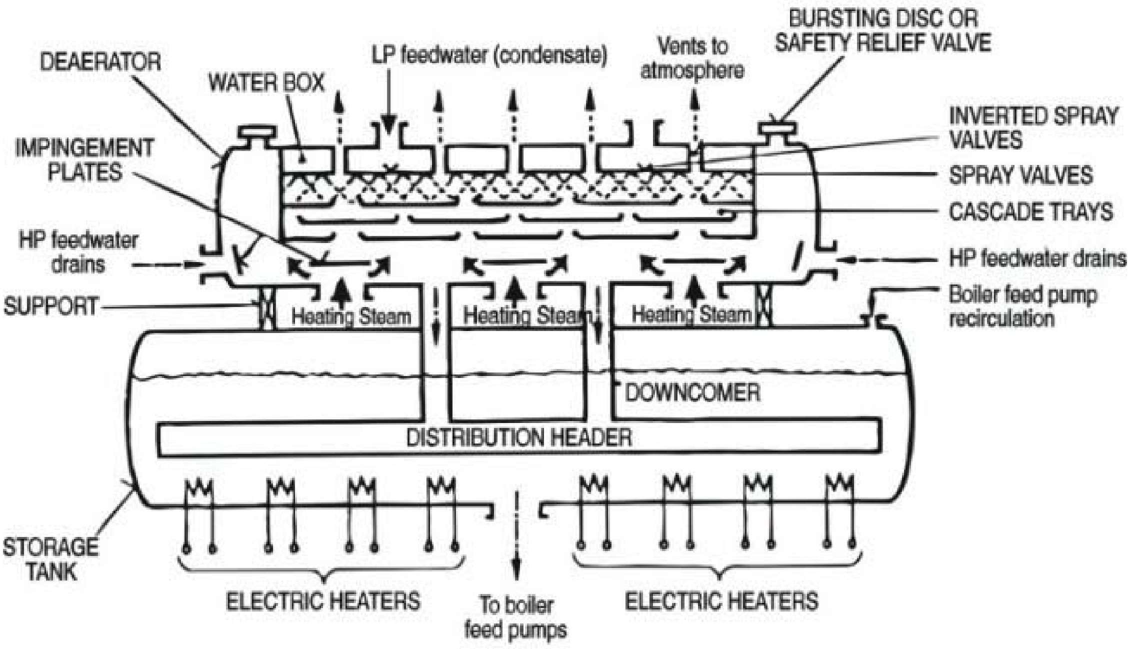

Figure 1: Deaerator and deaerator storage tank

Immediately below the deaerator is the *deaerator storage tank* where a large quantity of feedwater is stored at near saturation conditions. In the event of a turbine trip the steam generator or boiler will require an assured supply of feedwater to maintain the required water inventory during subsequent stabilizing conditions while residual heat must be removed. During such conditions, the loss of extraction steam to the high pressure feedwater heaters renders them ineffective and water from the deaerator storage tank is pumped into the boiler or steam generator without further heating. If the pressure in the deaerator is between 0.5 MPa and 1.0 MPa then the corresponding temperature of this stored feedwater will be between 150°C and 180°C. With an adequate supply of water at this temperature in the deaerator storage tank damaging thermal shock to the boiler or steam generator is avoided.

The deaerator storage tank is usually located at a high elevation between the reactor or steam generating unit and the turbine hall so as to ensure an adequate net positive suction head at the inlet to the feedwater pumps so minimizing the risk of cavitation in the pump.

2.3. Feedwater Heaters

The *low pressure feedwater heaters* receive extraction steam from the low pressure turbine for heating the feedwater. Condensate extraction pumps pump condensate from the condenser hotwell, through the low pressure heaters and to the deaerator.

The *high pressure feedwater heaters* receive extraction steam from the high pressure (water cooled reactors) or intermediate pressure (conventional systems) turbines.

Feedwater pumps pump feedwater from the deaerator storage tank, through the high pressure heaters and to the boiler or steam generator.
The conventional design for a feedwater heater is that of a horizontal cylindrical shell inside of which is a bank of U-tubes connected to a divided header at one end as shown in Figure 2. Feedwater enters one side of the header, passes through the U-tubes and leaves from the other side of the header. Extraction steam from the turbine enters the shell and passes over the outside of the tubes where it is condensed. The condensed steam collects in the bottom of the shell and is drained away. Generally the drains from the high pressure heaters are cascaded via lower pressure heaters to the deaerator and those from the low pressure heaters likewise to the condenser.

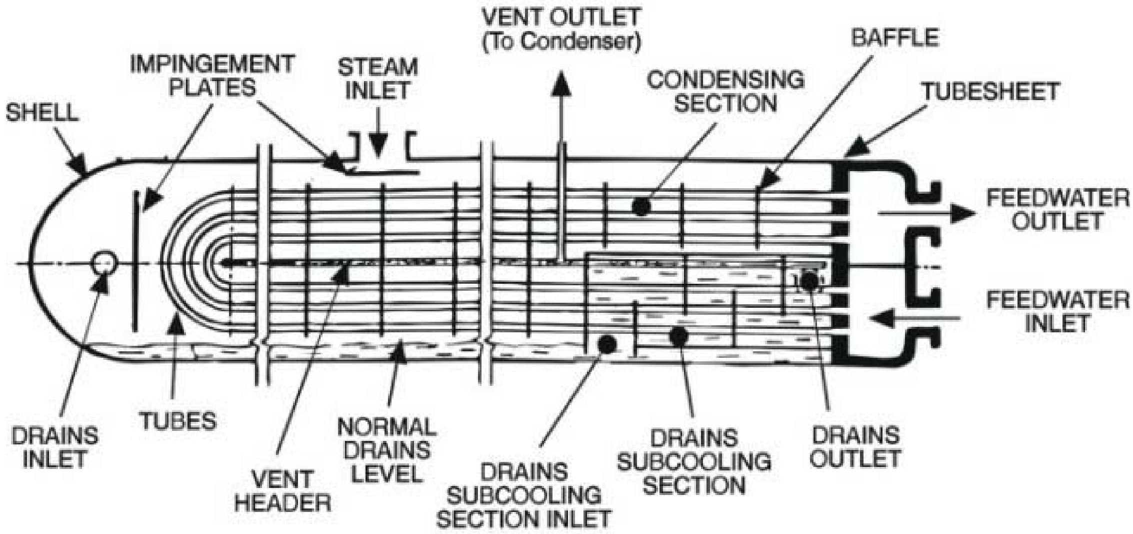

Figure 2: Feedwater heater with integral drains cooler

Like the reheaters and deaerator the feedwater heaters are self regulating and only draw as much extraction steam from the turbine as is required to heat the feedwater. The greater the flow of feedwater the greater the rate of heat absorption from the steam and the greater the flow of extraction steam.

In the event of a turbine trip, the steam supply to the turbine is cut off and pressures throughout the turbine decrease to condenser pressure. Extraction steam pressures follow suit inducing a reverse flow from the feedwater heaters to the turbine. The low pressure in the feedwater heater shell initiates vigorous flashing of any condensed steam. This may cause some water to become entrained in the reverse steam flow to the turbine. Any water entering the turbine in this way could cause severe damage to the turbine blading. As a precaution therefore, non-return valves are usually placed in the extraction steam lines between the feedwater heaters and turbine. These may be motor assisted to ensure sufficiently rapid closure at the onset of reverse flow.

3. Condenser

3.1. Introduction

The purpose of the *condenser* is to condense the exhaust steam from the turbine so that it can be returned to the system for reuse. In the Rankine cycle the condenser is complementary to the boiler in that it condenses the steam while the boiler boils the water. Like the boiler it has a free water surface that interfaces with the steam and some form of level control is required. Steam leaving the turbine enters at the top of the condenser and circulates around the outside of the tubes where it is condensed by cooling water passing through the tubes. The resulting condensate rains down to collect in a *hot-well* at the bottom of the condenser. Figure 3 and Figure 4 show the typical arrangement of a large condenser.

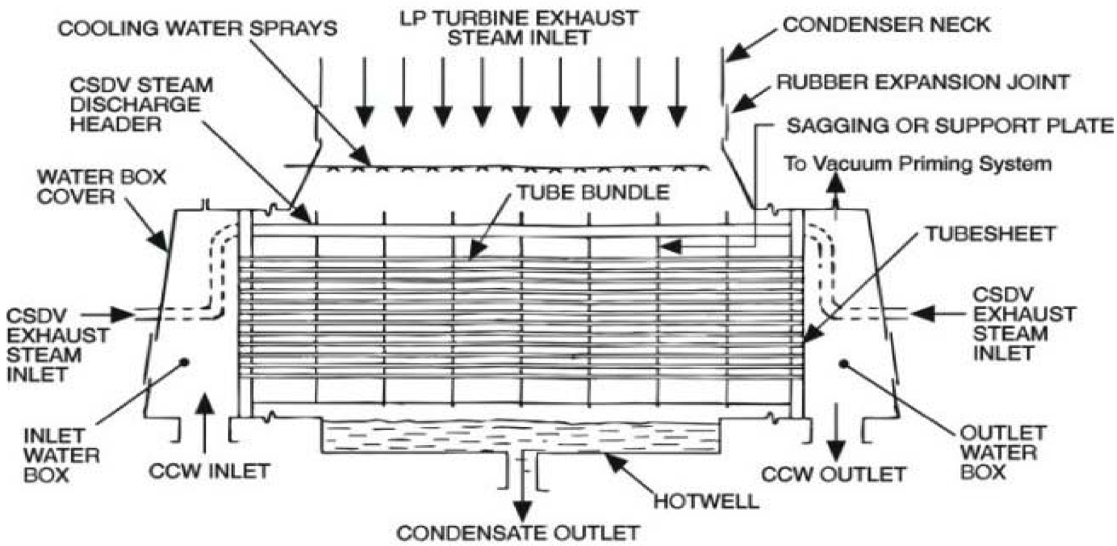

Figure 3: Condenser longitudinal section

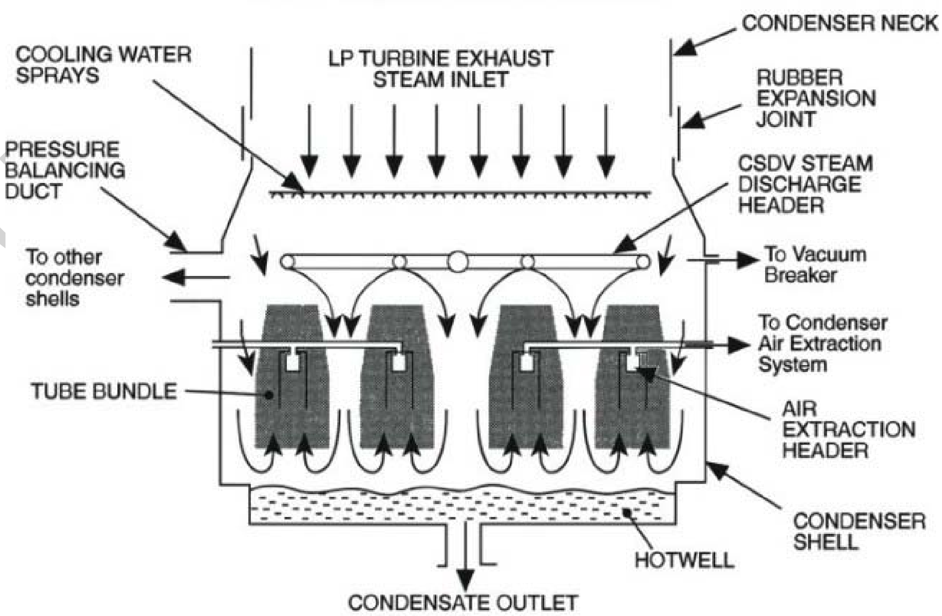

Figure 4: Condenser cross-section

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Bibliography

Black & Veatch (1996). *Power Plant Engineering*, Chapman and Hall.[This gives a good information on different types of power plants and their main components. It presents all basic aspects of power plant technology with separate topics by specialist authors. Emphasis on fossil fuel fired plants but has one chapter on nuclear energy.]

British Electricity International (1991). *Modern Power Station Practice*, Volume C, Turbines, Generators and Associated Plant, Pergamon Press.[Very comprehensive text directed towards the design and operation of both fossil fuel boilers and nuclear reactors as well as transmission systems. Provides basic theory and detailed description of large electrical generators]

Cottom K.C. (1993) *Evaluating and Improving Steam Turbine Performance*, Cotton Fact.[This gives detailed information on turbine performance based on actual practice with many examples of industrial tests.]

Elliott T.C. (1989). *Standard Handbook of Power Plant Engineering*, McGraw-Hill.[This gives good information on the basics of power generation with reference to different plant components.]

El-Wakil M.M. (1984). *Powerplant Technology*, McGraw-Hill.[Good general text on all aspects of power plant engineering including new and emerging technologies. Includes basic theory and description of equipment.]

Kearton W.J. (1961). *Steam Turbine Theory and Practice*, Pitman.[Excellent text on steam turbine design but now dated as it covers only smaller units.]

Khalil E.E. (1989). *Power Plant Design*, Abacus Press.[This provides a follow up of basic engineering cycles with applications to conventional power plants. It includes heat exchange and energy conversion equipment.]

Woodruff E.B., Lammers H.B. & Lammers T.F. (1998). *Steam Plant Operation*, McGraw-Hill.[This is a basic book on plant equipment. It illustrates various power plant components and describes their use and operation.]

Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.