Secondary Systems: Steam System

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In this lecture we shall discuss the layout of secondary system with emphasis on steam system, in a typical pressurized water reactor.

At the end of this session, learners will be able to
   (i) list the components of secondary system
   (ii) enumerate the role of individual components of secondary system
   (iii) understand the role and functioning of moisture separator
   (iv) enumerate the working of reheater

1 Secondary system of thermal (nuclear) reactors

The overall function of secondary system is to ensure regulated supply of steam to various turbine units, condense the spent steam from turbines and process the condensate to a condition suitable for re-use in the steam generator as the secondary coolant.

The secondary system of a typical Pressurized Water Reactor comprises two important subsystems: (a) steam system & (b) condensate/feed water system. The secondary system of PWR is located outside the containment and does not contain any radioactive material. The steam generated in a Boiling Water Reactor is slightly radioactive with N-16 being the major isotope with a half-life of 7 seconds. Hence the secondary system of BWR is shielded to protect plant personnel from exposure to radiation during the normal operations. The short half-life of N-16 makes the secondary system accessible to maintenance within a short duration of reactor shutdown.

1.1 Layout of secondary system

The outlet of steam generator represents the beginning of secondary system. Multiple parallel lines are used to supply steam from (steam) generator to the high-pressure turbine. The steam leaving the high-pressure turbine enters the moisture separator and reheater, before being directed to the low-pressure turbines. The exhaust steam from low-pressure turbine is condensed using the cooling water circulated in the condenser. The condensate is pumped through clean up system and low-pressure heaters using the condensate pump. The main feedwater pump is used to pump water obtained from low-pressure heaters to high-pressure heater, from which water is supplied as secondary coolant to the steam generator. A schematic layout of secondary system is shown in Figure 1.
1.2 Important components of secondary system

From the layout of secondary system shown in Fig. 1, the following may be identified as important components of secondary system:

1.2.1 Valves

A number of valves including safety valves, isolation valve and throttle valve are located in the pipelines connecting steam generator with high-pressure turbine. The isolation valve located outside the containment is used to isolate the reactor from turbine section, in case of a requirement. Safety valves ensure that the pressure in the pipelines carrying steam from generator to high-pressure turbine is within permissible limits, by bleeding the excess steam responsible for pressure increase. Throttle valve is used to regulate the flow rate of steam entering the high-pressure turbine.

1.2.2 Turbines

The conversion of thermal energy of high-pressure steam to mechanical energy is accomplished in turbines. These turbines drive the generator connected to them via a common shaft rotated by steam impinging on turbine blades.
In a typical PWR, the steam entering the high-pressure turbine is saturated at about 6.68 MPa with moisture content of about 0.25 %. Here it is important to note the difference in the quality of steam produced in a thermal power plant using fossil fuels and that produced in steam generator of nuclear reactor. In fossil-fuel operated power plants, steam is available at very high pressures (16-17 MPa) and temperature (540 C). Supercritical boilers produce steam with much higher pressures (25 MPa). The lower steam pressure results in its higher specific volume. This means that 1 kg of steam obtained from SG of a PWR occupies more volume than 1 kg of steam of obtained from boiler of a typical thermal power plant. The total energy content of a wet steam is lower than that of dry steam. Hence to perform an estimated work, higher mass of steam is required if it is wet. The wet nature of steam from PWR combined with lower pressure leads to higher steam requirement, both in terms of mass and volume, when compared to that required for a typical thermal power plant. For instance, a 1000 MWe thermal power plant requires 800 kg/s of steam while that of a 1000 MWe PWR would require 1700 kg/s of steam.

The higher volumetric flow rate of steam in PWR requires turbines with blades of larger diameter and length. To maintain the blade tip speed (πDN) within limits, larger diameter blades must be run at lower speeds. Hence for a fixed frequency, say 50 Hz, the turbines in nuclear power plants are run at speed, which is 50 % of turbine speed in thermal power plants.

The high-pressure turbine used in PWR is normally of double-flow type. Depending on the number of exhausts in turbines, they are classified as single-flow type and double-flow type. In single-flow type, steam enters at one of the turbine, expands by performing work and leaves at the other end of the turbine. With the use of large volume of steam and high pressure drop across the blades incurred, there exists an imbalance of axial forces on the rotor. This can be circumvented by supplying steam at the centre of turbine and allowing the same to expand in both directions with exhaust located at both the ends of turbine. The axial force exerted on the rotor at one end is balanced by those exerted on the rotor at the other end. Such turbines with steam inlet at the centre and one steam exhaust at each end are called double-flow turbines.

Steam volume at the exhaust of high-pressure turbine is much higher than that at the inlet. Hence two, double-flow low-pressure turbines are required. The low-pressure turbines directly deliver exhaust steam to a condenser maintained at negative pressure. The use of negative pressure in condenser permits removal of larger amount of heat from steam in low-pressure turbines.
Example - 1: Steam at the rate of 500 kg/s boiler is produced in a boiler. The analysis of steam showed the presence of liquid water to the extent of 0.5 %. Determine the mass flow rate of dry steam.

Solution:

Let \(m_w\), \(m_s\) and \(m_{ws}\) be the mass flow rates of water, dry steam and wet steam respectively.

From the mass balance, \(m_{ws} = m_w + m_s\)

\[\% \text{ wet steam} = \frac{m_w \times 100}{m_{ws}} = \frac{m_w \times 100}{(m_w + m_s)}\]

Solving the above equation by setting \(\%\) wet steam as 5 \%, mass flow rate of dry steam is found to be 497.5 kg/s

Example – 2: The specific enthalpy of dry steam and saturated water at 6.8 MPa and 285 C (saturation pressure and temperature) are 2773 kJ/kg and 1262 kJ/kg respectively. If the dryness fraction of steam is 99 \%, determine the specific enthalpy of wet steam.

Solution:

Dryness fraction, \(x_d = 0.99\)

Specific enthalpy of dry steam, \(h_g = 2773\) kJ/kg

Specific enthalpy of saturated water, \(h_i = 1262\) kJ/kg

Specific enthalpy of wet steam, \(h_{ws} = x_d h_g + (1-x_d)h_i = 0.99 \times 2773 + 0.01 \times 1262 = 2757.89\) kJ/kg

Therefore, specific enthalpy of steam with 99 \% dryness under these conditions is 2757.89 kJ/kg.

1.2.3 Moisture separator

The wetness of steam increases as it is expanded in high-pressure turbine. The presence of moisture in the steam leads to corrosion of turbine blades, apart from reducing the energy of steam that can be recovered (lower turbine efficiency). Hence the moisture content of steam or in other words, the wetness fraction of steam must not be greater than 10 \% during its transit in any of the turbines (high-pressure or low-pressure) to avoid damage to turbine blades.
The spent steam from high-pressure turbine is directed to the moisture separators and then to reheaters. In some designs, moisture separator and re heater are integrated into a single unit named moisture separator reheater (MSR). Stand-alone moisture separators work by imparting centrifugal motion to steam-water mixture through use of vanes. This causes moisture to be disengaged from the wet steam. A schematic diagram of stand-alone moisture separator is shown in Fig. 2.

![Schematic diagram of stand-alone moisture separator](Redrawn from Ref. [4])

In MSR systems, moisture is separated from the steam by directing steam-water mixture through chevron type plates that cause steam to change flow direction rapidly. A schematic diagram of moisture separator in integrated MSR systems is shown in Fig. 3.
1.2.4 Reheater

In the preceding section, we have realized the importance of maintaining a lower wetness fraction of steam to prevent corrosion of turbine blades as well as to achieve higher turbine efficiency. Though moisture separators remove majority of moisture, reheaters are required to improve dryness fraction or quality of steam.

Reheaters utilize finned tubes as heat transfer surface. The hot fluid for reheaters is the high-pressure steam from the steam generator and passes inside the finned tubes. In PWR, high-pressure steam at 5.5 MPa is used for this purpose. The exhaust steam after passing through the moisture separator flows outside the tubes. Though both the high-pressure steam used for heating and the exhaust steam are saturated, a temperature difference of about 100 exists between the two streams due to difference in their pressures. The exhaust steam gets superheated upon thermal contact with the high-pressure steam thereby becoming dry vapors. The heat transfer coefficient for heat transfer involving dry gas or vapor is low. Hence, finned tubes are used to increase the heat transfer area to compensate for lower heat transfer coefficient. The temperature of exhaust steam after reheating reaches within 20° of the hot stream used for reheating and is suitable for feeding to low-pressure turbines. The high-pressure steam used for reheating condenses inside the tubes and is supplied to high-pressure (feedwater) heater as the hot fluid. The schematic diagrams of MSR and stand-alone reheater are shown in Figures 4 and 5.
Fig 4. Schematic diagram of moisture separator reheater (Modified from Ref. [6])

Fig 5. Schematic diagram of stand-alone reheater

2 References/Additional Reading

5. http://www.kntc.re.kr/openlec/nuc/NPRT/module2/module2_5/module2_5_2/2_5_2.htm