NUCLEAR REACTOR STEAM GENERATION

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Summary

In certain types of water cooled nuclear reactors steam is generated directly in the reactor core. The steam is separated from the remaining water and sent directly to the steam turbine. In other types of water cooled nuclear reactors steam is generated in a separate heat exchanger or steam generator using the reactor coolant as a heat source. For the reactor the steam generator serves as a heat sink which is an important consideration in the event of abnormal transients or accident conditions. Steam generators serving water cooled nuclear reactors have unique design and operating considerations.

In gas cooled nuclear reactors there are also steam generators in which heat is transferred from the hot gaseous reactor coolant to the water-steam circuit. These however are more like once through fossil fuel fired boilers. The steam is generated in coiled tubes in a single pass through the steam generator. Superheated steam is produced and the water-steam circuit is very much like that of conventional fossil fuel

fired power plants.

Steam generators as used in water cooled nuclear reactors must operate under high rates of heat transfer with minimal temperature difference between the heating and heated fluids. Furthermore the volume of each fluid is relatively small compared with the total flows so they are prone to transient disturbances with changes in load. Of particular importance is the control of the water level and the separation of steam from the water within the steam generator.

The steam system serves not only to convey steam to the steam turbine but also to remove heat from the steam generator during shutdown and under abnormal operating conditions. This means that, even when the steam turbine cannot receive steam, there must be a removal path for it. It may be discharged to the atmosphere but this is wasteful so it is usually dumped into the turbine condenser. Here the surplus heat is removed by the condenser cooling water. Although this is not a desirable mode of operation it does enable a mismatch in load between the nuclear reactor and the steam turbine to be sustained for a period of time.

1. Steam Generation

1.1. General Characteristics

In the BWR and LGR (RBMK) steam is generated directly within the core of the reactor whereas in all other reactors steam is generated in a separate steam circuit. Generating steam directly requires that the coolant be light water so this is only possible with certain types of reactors. It also means that the reactor must be able to be operated and cooled satisfactorily with a coolant that changes phase. A further implication is that the steam leaving the reactor is slightly radioactive due to the activation of its oxygen nuclei and the production of nitrogen-16. This activity is however short lived and soon decays to immeasurable quantities. Any fission products released from the fuel however may get carried through the entire steam and water circuit thus necessitating additional precautions during operation and maintenance.

When steam is generated in a separate secondary circuit the coolant in the primary circuit remains isolated from the reactor. This has the advantage of better containment of radioactive products in the event of fuel leaks. It does however complicate the overall system as a separate steam generator has to be provided. This is effectively a heat exchanger between the primary and secondary circuits for transferring heat from the reactor coolant to the steam system.

When steam is generated directly within the reactor the conversion of water to steam results in the formation of vapor voids of lesser density within the liquid. Since the water serves as a moderator this change in density has an effect on the neutron flux and hence the rate of heat generation. In a reactor which is optimally moderated or under moderated the formation of voids will decrease the degree of moderation of the neutrons. At the resulting higher neutron energies the fission cross section is less and the reaction rate will be lower. This results in a decrease in the heat generation rate and reduction in degree of boiling. This negative feedback effect has a self stabilizing effect on the reactor power. In a reactor which is over moderated the result is a slight positive feedback effect which can lead to instability if not offset by other negative reactivity effects.

An important aspect of steam generation is the separation of the steam from the water. Nuclear reactors generally have high heat release rates per unit volume and a large quantity of circulating coolant. It follows that, whether the steam is generated within the reactor or in a separate steam generator, it is advantageous to extract the steam from the water as effectively as possible. This is usually achieved by extracting about 10 percent to 15 percent by weight of the steam and recirculating the water over the reactor fuel rods or steam generator tubes. This actually represents 70 percent to 80 percent by volume at prevailing pressures due to the difference in density between the steam and water. Separation is effectively achieved by cyclonic separators followed by mesh or chevron type dryers. The resulting steam generally has a moisture content of only about ¼ percent.

During steam separation non-volatile impurities are left behind in the water. Their concentration gradually builds up in the reactor or steam generator and provision must be made for removal of some water, by way of blowdown or other mechanism, for chemical treatment.

1.2. Circulation in Boiling Water Reactors

In boiling water reactors steam is generated directly from the light water coolant which circulates through the core of the reactor. The circulating flow is driven by a number of jet pumps located in an annulus around the periphery of the reactor. External recirculation pumps draw coolant from the reactor vessel and supply the jet pumps with the driving flow necessary to induce a larger volume upward flow through the core of the reactor. About 14 percent of the water flowing through the core is converted into steam while the remainder is returned to the jet pumps.

A characteristic of the boiling water reactor is the ability of being able to control power output by varying the coolant flow rate through the core. This in turn is controlled by the external recirculating flow supplied to drive the jet pumps. Boiling in the reactor core produces voids which in turn reduce the moderating effect and hence the power production. A certain degree of voidage will give a particular power output. If the coolant flow rate through the core is increased the quality of the steam at the outlet will be momentarily lowered as the increased flow rate will produce a lesser increase in enthalpy for the same heat absorption. The reduced voidage arising from this will increase the neutron moderation and hence the power production. This will then produce more steam and the quality will be raised to a new equilibrium value. The final steam quality will be near the original value before the increase in flow but the power will be at a new and higher level. This mechanism allows for changes in power output of up to 25 percent full load without movement of the control rods.

1.3. Steam Generation in CANDU Reactors

Although CANDU reactors have pressurized primary coolant systems where boiling is suppressed, local boiling does occur in the highest rated fuel channels. The steam produced is subsequently partially condensed when it mixes with coolant from lower rated fuel channels. This has some definite advantages. Slight boiling enhances the heat transfer coefficient on the fuel element surfaces thus promoting heat transfer. It also increases the heat removal capacity of the coolant as the enthalpy of the mixture leaving the fuel channel is greater. Thirdly, after mixing with coolant from non-boiling fuel channels, the average coolant exit temperature is at saturated conditions or closer to saturated conditions than it would be if there were no boiling. Thus the coolant entering the steam generators is at as high a temperature as possible considering the prevailing pressure in the system. The degree of boiling is limited to about 3 percent by weight to avoid flow instability problems and to maintain a sufficient margin to dryout of the fuel elements. This small amount of steam is nevertheless about 25 percent by volume at prevailing pressures and is not insignificant as far as reactivity effects are concerned as it does give a slight positive feedback effect. This is due to the fuel channel spacing being greater than optimum resulting in overmoderation of the neutrons. Voidage reduces the moderating effect and reduces neutron absorption thus creating conditions closer to the optimum. This positive feedback effect is however counteracted by other negative feedback effects so that changes in power are not as significant as they are in the boiling water reactor.

1.4. Steam Generators

Steam generators serve to transfer heat from the reactor coolant circuit to the turbine steam system. As such they are simply large heat exchangers. For the secondary side, the steam generator serves as a source of heat to generate steam for the thermodynamic cycle. For the primary side, the steam generator is heat sink to which heat is rejected during both normal and abnormal conditions.

This has important safety implications considering that the nuclear reactor continues to generate heat from the decay of fission products for a considerable time after being shutdown. During operation and immediately after shutdown this *decay heat* is 6 percent to 7 percent of the full power heat production.

In a nuclear plant with an electrical output of 1000 MW the reactor produces approximately 3000 MW of heat and the decay heat amounts to nearly 200 MW. This is a substantial amount, the removal of which must be guaranteed under all conditions including for a certain period after shutdown since it takes some 10 hours for this to fall to a tenth of the initial value, that is, about 20 MW for the example given.

Separate smaller capacity heat removal systems are able to handle these lesser heat flows after the reactor has been shut down for some time.

The heat transferred Ω in the steam generator is governed by the following basic equation:

$$\Omega = U\,A\,\theta \qquad (1)$$

Here *U* is overall heat transfer coefficient, *A* the surface area and θ the temperature difference between the primary and secondary fluids. The overall heat transfer coefficient depends mainly upon the individual heat transfer coefficients h on each side of the tubes since the conductivity of the tubes is generally good. The surface area *A* is physically constant but can be effectively reduced if portions of the tubes are uncovered due to a low water level on the steam generating side. It is really the heat transfer coefficient that changes when the tubes are no longer flooded with water but it is easier to visualize this as a loss of heat transfer area.

For effective removal of heat there must be an adequate but not excessive temperature difference θ. This can be controlled by varying the pressure on the steam side of the steam generator and hence the corresponding saturation temperature.

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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.