OPTIONS AND CHALLENGES OF STEAM CYCLE COMPONENTS FOR SCWR

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Abstract

The steam cycle of supercritical water cooled reactors (SCWR) is intended to be based on the experience with supercritical fossil fired power plants and on boiling water reactors. Different steam cycle concepts have been proposed up to now for the SCWR, and its key components are discussed in more detail here. These are the turbine design, the reheater or steam separator design, the design and operation of the start-up system, the feedwater line with 7 preheater stages, the feedwater tank and the high pressure feedwater pumps. The paper highlights the design features, discusses the thermal-hydraulic and technical challenges and summarizes recent achievements.

1. Introduction

The basic strategy to develop supercritical water cooled reactors (SCWR) is to use the long term experience of pressurized water reactors and of boiling water reactors on one hand, and the experience with fossil fired power plants designed for supercritical steam conditions on the other hand, to derive a novel plant concept with a minimum of research needs. Obviously, the reactor core of such a SCWR will be basically new then, such that core outlet temperatures as well as the enthalpy rise of coolant in the core will be exceeding by far the current light water reactor experience. As a consequence, most of the recent publications were focusing on a suitable core design up to now, which are summarized e.g. by Oka et al. [1] for their Super Light Water Reactor concept and their Super Fast Reactor concept, or by Schulenberg et al. [2] for the High Performance Light Water Reactor (HPLWR). The concept of the safety system may be based on those of boiling water reactors, but it has to be modified for the once through steam cycle without internal coolant recirculation, such that control of the coolant inventory in the reactor has to be replaced by a control of coolant flow in case of a loss of coolant accident. Examples are discussed by Oka et al. [1] and by Schlagenhaufer et al. [3]. With this paper, we rather like to draw the attention on all components outside the reactor containment to discuss their options and future challenges.

2. Comparison with fossil fired power plants at supercritical pressure

One of the latest and largest coal fired power plants in the world is unit K of the German power plant Niederaussem [4]. It is fired with lignite to produce a gross power output of 1012 MW and a net output of 950 MW with a net efficiency of 43.2%. With a life steam pressure of 26 MPa, a reheat pressure of 5.5 MPa and life steam and reheat temperatures of 580°C and 600°C, respectively, the gross power and pressures are comparable with the HPLWR [5]. The power plant is in commercial operation since 2003.

The evaporator, which is the tube wall of the boiler, wherein coolant is passing the pseudo-critical point at supercritical conditions, features 2 intermediate mixing stages to homogenize the coolant while being heated up. The maximum heat flux, provided by the flames, is less than 400 kW/m^2 to limit the post-dryout wall temperatures below ~550°C. All boiler materials are high Cr ferritic-martensitic steels [6]. The evaporator is followed by 6 parallel separators which serve as a start-up system at sub-critical pressure such that a minimum mass flow rate can be maintained in the evaporator at low power. In case that liquid is separated there, it is collected in a vertical vessel and re-supplied to the feedwater line, upstream the economizer, via a recirculation pump. Four superheater stages with intermediate coolant mixing each and coolant injectors before the last superheater stage, minimizing the peak coolant temperature, bring the steam temperature up to 580°C. The reheater is designed as tube bundles inside the boiler house with 2 heat-up stages and a mixing and coolant injection system in between. A single flow high pressure turbine, a double flow medium pressure turbine and two double flow low pressure turbines form the turbine train running at full speed of 50Hz. The steam cycle is operated with sliding pressure above ~40% thermal power, such that the steam valves are kept open and the life steam pressure is decreasing almost proportionally with the feedwater mass flow rate while lowering the power. The high pressure steam mass flow rate at full power is ~800 kg/s. 10 preheater stages produce a feedwater temperature of 293°C at 31.2 MPa. A feedwater tank at 1.5 MPa serves as preheater 7.

Taking such a power plant design as a starting point for SCWR development, we have to consider the following basic differences of the nuclear system:

- Intermediate coolant mixing in the core like in the boiler has been tried by Schulenberg et al. [2] to some extend in their 3 pass core concept. Even such mixing, however, will not be as homogeneous as in the boiler design, so that hotter peak coolant temperatures must be expected in the reactor. A detailed evaluation and assessment of peak coolant temperatures have been given by Schulenberg et al. [19].
- The peak heat flux of a fuel rod with 39 kW/m linear power and with an outer cladding diameter of 8 mm is 1550 kW/m^2, which is almost 4 times the maximum heat flux of the boiler tubes, so that a sliding pressure operation with post-dryout conditions in the core must definitely be avoided.
- Steam extraction to a start-up system at the evaporator outlet and a nuclear reheater inside the core are complicating the core design significantly, at least in a pressure vessel type reactor, so that other options must be considered for start-up and re-heat in the nuclear system.
- The lower core outlet temperature of 500°C of the HPLWR design [2] and limitation of the reheater (as discussed below) are easing the material requirements of the turbines, but result in a higher steam mass flow rate of ~970 kg/s at comparable turbine power.
- Last but not least, the containment as the outer safety barrier, the protection of the activated steam in the entire steam cycle and a residual heat removal system are requirements which are not foreseen in any fossil power plant, causing some further basic differences.

Nevertheless, however, the basic technologies needed to build the nuclear supercritical steam cycle components are still considered to be similar as those of the fossil fired plant and synergies could be gained.

3. Thermodynamic options

The steam cycle of the HPLWR has been optimized by Brandauer et al. [5] for steady state, full load conditions using the thermodynamic code IPSE-Pro 4.0. Their result is shown in Fig. 1, which will be used as a reference in this paper. Aiming at a net power output of 1000 MW_e, which was rather an arbitrary target definition than a result of an optimization, the reactor has to produce a thermal power of 2300 MW_{th} which results in a net efficiency of 43.5%. Like in Niederaussem, a high pressure (HP), medium pressure (IP) and low pressure (LP) turbine train is foreseen with a reheater between the HP and the IP turbine.

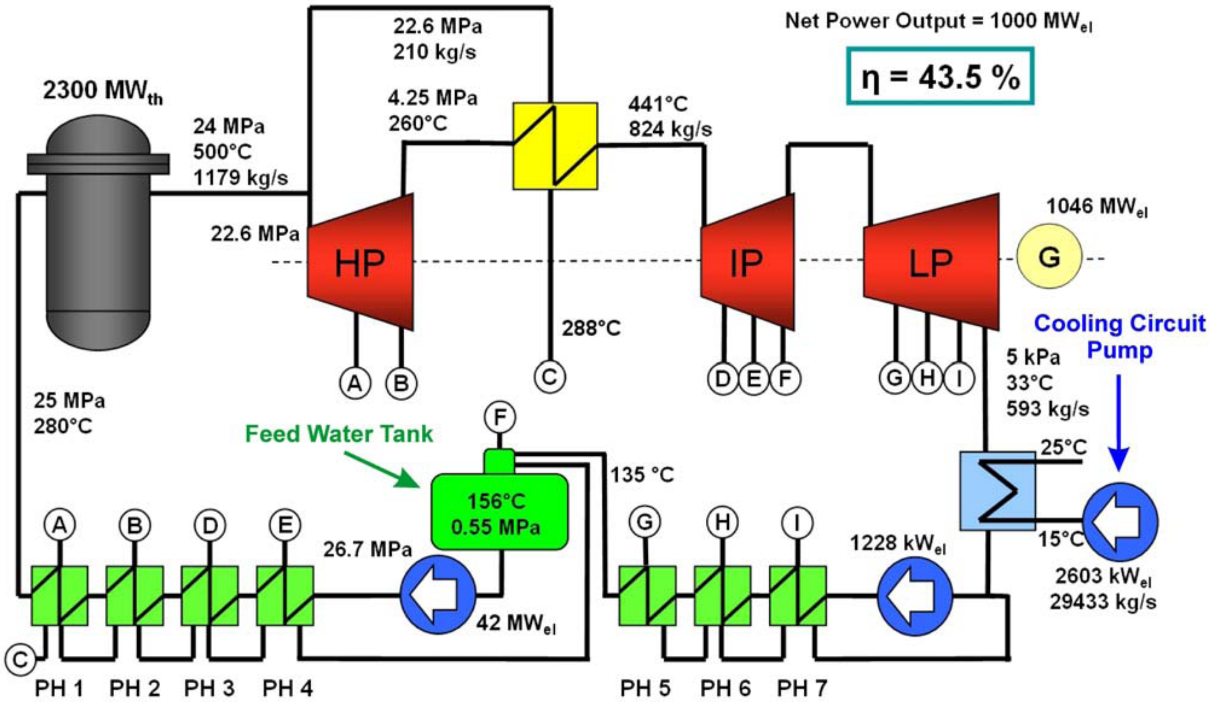

Fig. 1: Schematic diagram of the HPLWR steam cycle [5].

Different from coal fired power plants, a steam fraction of 210 kg/s is extracted upstream the HP turbine to reheat the steam after the HP turbine. This extracted steam is cooled down to 288°C and thus changes its properties from steam like to liquid like conditions. Due to the non-linear cool down curve on the hot side, the IP steam on the secondary side can only reach a temperature of 441°C at maximum [5]. The reheat pressure of 4.25 MPa has been optimized such that condensation in the HP turbine will be avoided with some margin. Thus, a moisture separator as needed for the saturated steam cycle of boiling water reactors will not be required. The thermodynamic optimum of the cycle efficiency was at a slightly lower reheat pressure of 3.9 MPa, as discussed by Herbell et al. [7]

Oka et al. [1] as well as Bogolovskaya and Abdulkadyrov [8] discuss the alternative option to place the reheater between the IP and the LP turbines at 0.28 MPa. As the IP turbine will expand into the two-phase region in this case, they propose to use a moisture separator and two reheaters, one of which will be heated by steam extracted inside the HP turbine and a second one by life steam extracted upstream the HP turbine.

An interesting alternative has been proposed by Yamada et al. [9]. If sufficient moisture can be extracted inside the LP turbines, the reheater can completely be omitted and simply a moisture separator at 1.1 MPa, between the IP and the LP turbines, is considered to be sufficient. Such a solution, however, is strongly dependent on the IP and LP turbine design which has to stand the increased moisture level. Ideas to reheat the IP steam inside the reactor, as proposed for pressure tube reactors by Duffey et al. [10], are not considered to be applicable for pressure vessel type reactors as different pressure levels would require a significant mass of steel structures inside the reactor core.

The feedwater line, shown in Fig. 1, includes 8 preheater stages of which the feedwater tank at 0.55 MPa serves as one of the preheater. The high pressure condensate left over from the reheater is added to the final, high pressure preheater PH1. Besides its function as a water reservoir and expansion vessel, the feedwater tank serves also as a deaerator. As an interesting alternative, however, Bogolovskaya and Abdulkadyrov [8] propose to design the feedwater line without any feedwater tank and to use an enlarged hotwell of the turbine condensers as feedwater reservoir and deaerator instead.

4. Conceptual design of major components

A number of detailed design studies have been performed for the reference cycle described in Fig. 1, as will be discussed next.

4.1 Steam turbines

Following the overall design strategy as mentioned above, the design intent of the HPLWR concept was to use proven and reliable components of supercritical fossil fired power plants as far as possible. A suitable turbine design concept, shown in Fig. 2, has been discussed by Herbell et al. [11] based on state of the art steam turbines of fossil fired power plants. Like there, the turbine train may run at full speed of 50 Hz.

At the given condenser pressure of 5kPa, the last stage of the LP turbine will need an axial exhaust area of 12.5m^2. The three double flow LP steam turbines, with a bearing distance of 9.2m and an estimated weight of 350t each, are designed with 7 stages per flow. Also for the IP turbine, a comparable unit to those of supercritical fossil-fuelled power plants can be implemented. The proposed turbine is a double flow unit with asymmetric extractions at different pressures, including blade heights from 137 mm to 287 mm and a rotor with 1200 mm diameter at the last stages. Ten stages are needed for generator side flow, and nine stages are housed on the turbine side.

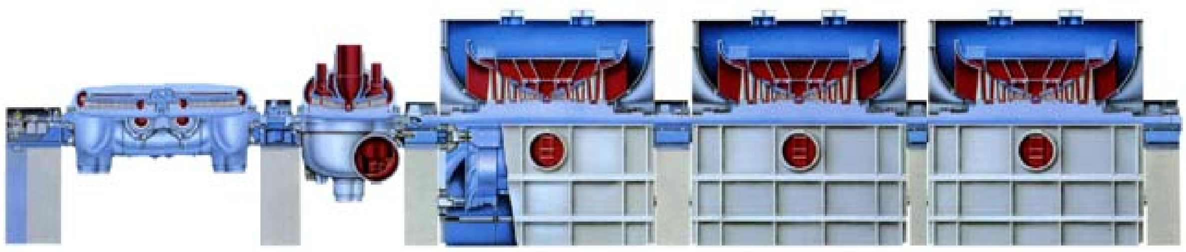

Fig. 2: Turbine design concept with double flow HP, IP and 3 LP turbines [11]

It is only the HP turbine that exceeds the dimensions of current HP turbines with its mass flow of 970 kg/s and its power of 320 MW. Herbell et al. [11] propose to use a double flow HP turbine having the advantage of axial thrust compensation. It would have to be designed particularly for this purpose, which is not expected to be a major challenge though. Steam inlet temperatures will even be around 100°C lower than those for supercritical fossil fired power plants. 17 turbine stages with a blade height of 48 mm at the inlet, increasing to 139 mm at the outlet could yield a rotor with 840 mm max. diameter and a bearing distance of 6.5m.

4.2 Reheater

A vertical reheater design concept with straight tubes has been proposed for the HPLWR by Herbell et al. [7]. Two parallel reheaters with 20m total axial length, 15m tube length and an outer diameter of 3m provide a heat transfer surface area of 6868m^2 each. Due to the supercritical pressure on the hot side, the thickness of the tube sheet becomes the limiting parameter which should not exceed 800 mm because of manufacturing constraints and to limit transient thermal stresses. If arranged horizontally, this reheater should slightly be inclined to avoid parallel channel instabilities.

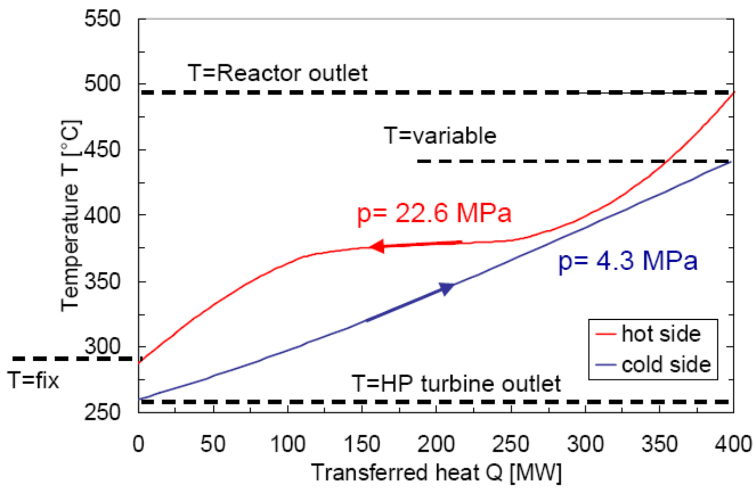

Fig. 3: Temperature vs. transferred heat of the reheater concept [7].

As indicated in Fig. 3, the axial temperature profile on the hot side is highly nonlinear, which reflects the transition from steam like to liquid like conditions at supercritical pressure, which could be described as pseudo-condensation. On one hand, this effect limits the achievable outlet temperature of the IP steam to around 440°C at a given reactor outlet temperature of 500°C. On the other hand, it includes heat transfer effects on the high pressure side with highly non-linear fluid properties. Herbell et al. [12] studied such heat transfer in more detail using test data obtained with supercritical CO_2 as a reference. They show that a deterioration of heat transfer may occur also under cooling conditions due to an obvious laminar flow even at Reynolds numbers up to ~20,000. Even though such Reynolds numbers are outside the range of the proposed reheater concept, further experimental studies with supercritical water under cooling conditions are recommended to confirm this unexpected flow effect.

4.3 Feedwater pumps

A set of 4 parallel feedwater pumps are recommended for the HPLWR concept, of which 3 are providing the full load mass flow rate of 1179 kg/s and a number 4 unit is kept on hot stand-by to continue operation in case of a pump trip. They shall provide a feedwater pressure of 26.7 MPa under nominal conditions. High pressure, multistage centrifugal pumps designed for supercritical fossil fired power plants can be used for this purpose, in principle, except that this nuclear application will require a leak tight enclosure. Type CHTD high pressure barrel casing pumps of KSB [13] are typical examples which could be qualified for the HPLWR.

Note that the feedwater pumps are the only coolant supply for the core. There is no primary or recirculation pump foreseen in a SCWR and a simultaneous trip of all coolant pumps would cause a loss of coolant in the core. In this case, the reactor needs to be depressurized to maintain the flow rate, either by blow down of steam to the condensers or, under accidental conditions, to the depressurization chamber of the containment. An extended coast down time of the pumps, e.g. provided by flywheels, does not help in these cases. The parallel feedwater pumps need to be equipped with check valves to avoid backflow in case of a trip of a single pump, and the feedwater penetration through the containment is closing passively by check valves as well. These check valves will make the pumps ineffective at lower speed.

4.4 Feedwater tank

The feedwater tank for the HPLWR steam cycle has been designed by Lemasson [14] for a maximum water volume of 350m^3 at a nominal pressure of 0.55 MPa. Steam which has been extracted at the outlet of the IP turbine is released here through spargers in a horizontal tube inside this tank. The feedwater line as well as the condensate lines from high pressure preheaters are supplying water to the tank under all load conditions. During the start-up phase, the start-up system described in chapter 5.2 and condensate bypass lines from both preheaters PH1 are supplying additional water and are thus heating up the water reservoir in the tank. A vent pipe connected with the tank serves as a deaerator to remove gas arising from the steam extractions. Finally, the feedwater tank controls the inlet pressure head of the feedwater pumps to avoid a booster pump. Fig. 4 shows an example how this tank could be designed.

The tank is divided into 3 compartments which are connected by penetration holes. This minimizes droplet entrainment from the spargers into the vent line or bubble entrainment into the supply lines of the feedwater pumps but still provides a cross flow, and thus shall provide sufficient coolant mixing to keep the entire water volume at saturation temperature. A co-axial feedwater line, coming from the upstream preheater PH5 is cooling the exhaust pipe to condense steam extracted with the non-condensable gas. On a closer look, however, the analysis of two-phase flow structures inside the feedwater tank is still a challenge.

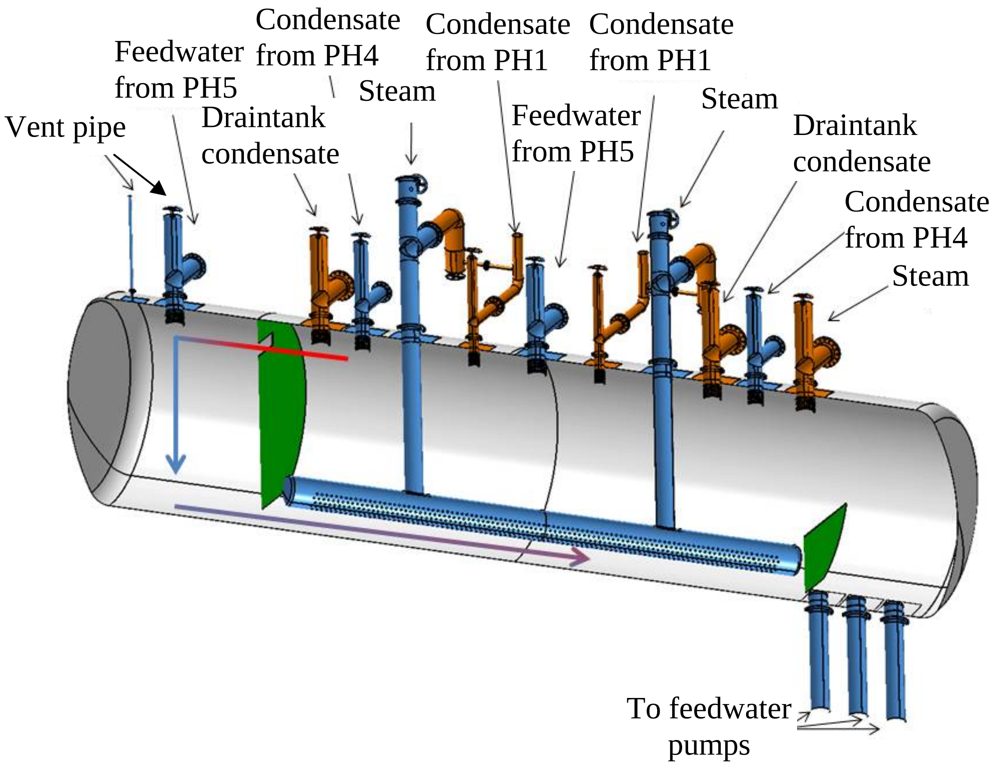

Fig. 4: Design concept of the feedwater tank [14]

4.5 Feedwater preheaters

Two lines of preheaters, with 7 U-tube heat exchangers each, have been proposed for the HPLWR plant concept [15]. The high pressure preheaters, PH1 to PH4 in Fig. 1, have an outer diameter of 2m to 2.5m and a length of up to 12.3m, of which PH1 is the largest component. Fig. 5 shows a cut away view of PH1. Steam which has been extracted from the steam turbines is entering the tube bundle from the top. As this steam is still superheated, is has to be cooled down first to the saturation temperature in the upper quarter of the preheater. A steam jet impinging on the tube bundle should be avoided because of the risk of corrosion-erosion. Condensate from upstream preheaters or from the reheater is entering from the right and evaporating again at the lower pressure. The steam is condensing on the tube outer surfaces and is finally sub-cooled in a compartment in the lower half of the preheater. Like with the reheater, the limiting component of this heat exchanger is the tube sheet which should not exceed 800mm thickness. The tube weldings can be inspected from the inlet and outlet plenums through a man-hole. These components are quite similar to those in fossil fired power plants so that major challenges are not expected. The low pressure preheaters are smaller and thus even less challenging.

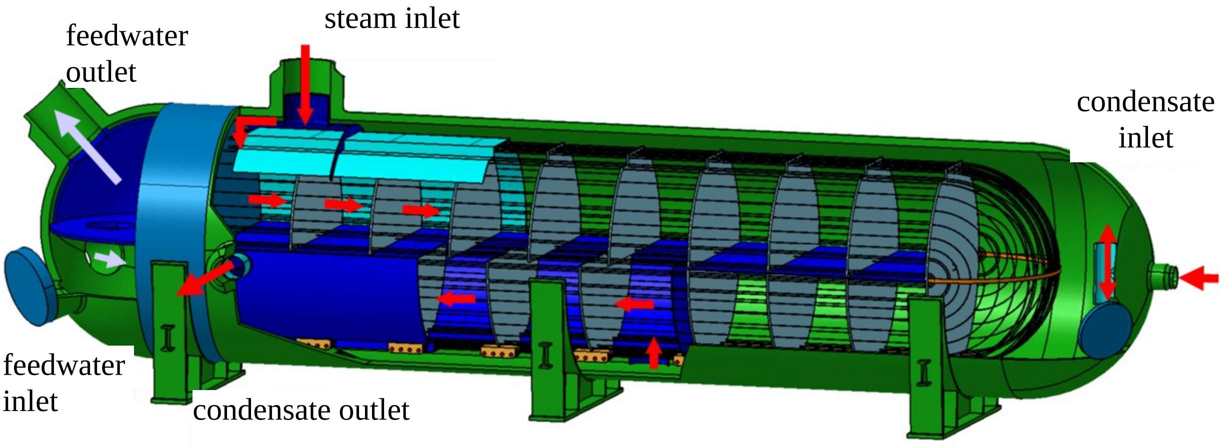

Fig. 5: Design concept of the high pressure preheater PH1 [15]

5. Control of the steam cycle

For discussion of the control of the steam cycle, we need to differ between the load range, when the turbine generator is connected with the grid, and a start-up range, when the system is pressurized, the thermal power of the reactor core is ramped up to a minimum power, an the components of the steam cycle are warmed up.

5.1 Control in the load range

Following a proposal of Schlagenhaufer et al. [16], the HPLWR should have load following capabilities at least between 50% and 100% of the nominal thermal power of the core. In this range, they propose to keep a constant, supercritical feedwater pressure of 25 MPa at the reactor inlet by control of the turbine valve. The steam temperature should be kept at the nominal temperature of 500°C at the reactor outlet to gain high part load efficiency, either by controlling the core power by the control rods and the steam temperature by the speed of the feedwater pump, as suggested by Schlagenhaufer et al. [16], or vice versa by controlling the core power by the feedwater pumps and the steam temperature by the control rods of the core. The latter option has been preferred by Oka et al. [1].

The reheat steam temperature at the inlet of the IP turbine can be kept at 441°C by a valve in the high pressure line downstream of the reheater, controlling the mass flow rate being extracted from the life steam. Fig. 6 shows these control loops in a simplified scheme.

The control system has been modelled by Schlagenhaufer et al. [16] with the system code APROS [17] to check its performance. Reactivity control has not yet been included in these analyses. Several additional control loops had to be added like liquid level control of the condensers by the condenser pump, condensate level control in the preheaters by their drain valves, and outlet temperature control of the cooling loop by the cooling pumps. No control has been foreseen, however, for the feedwater temperature at the reactor inlet and for the reheat pressure. Deloading the reactor from 100% to 50% of its maximum power, Schlagenhaufer et al. [16] show that the reheat pressure is decreasing from 4.25 to 2.2 MPa and the feedwater temperature is decreasing from 280°C to 245°C. The reason for both is the decreasing turbine inlet pressure at constant condenser pressure according to the elliptic law of steam turbines. The effect of this feedwater temperature swing on reactivity should be checked carefully in future studies.

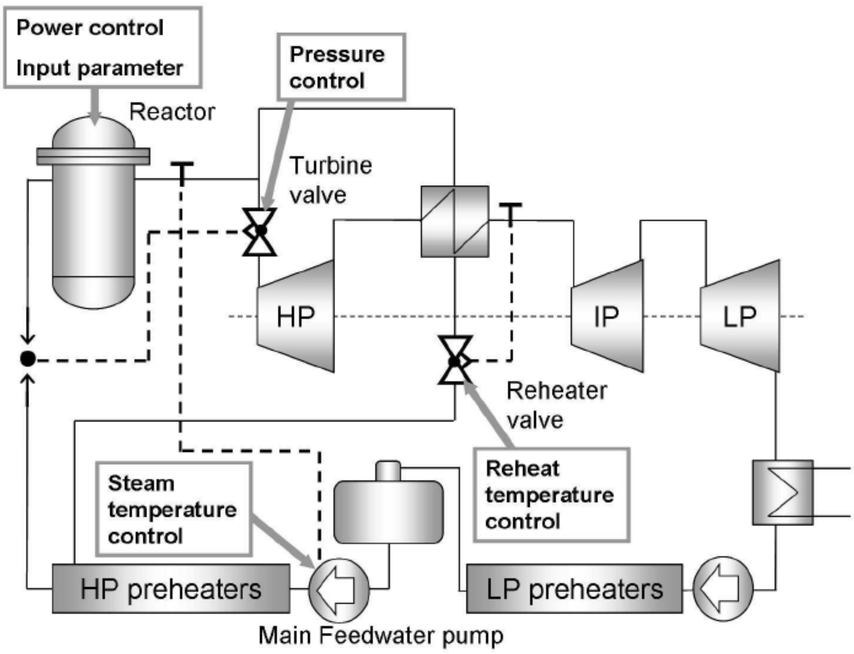

Fig. 6: Control loops for operation in the load range [16]

5.2 Start-up procedure

Trying to avoid two-phase flow for any thermal power of the reactor, except for residual heat removal, Schlagenhaufer et al. [18] propose to pressurize the reactor to 25 MPa already under cold conditions. Once the reactor became critical, it produces at first only hot water (liquid) which cannot be supplied to the turbine. Therefore, in order to avoid turbine erosion, water or steam from the reactor is considered to by-pass the turbines for any thermal power below 50% of the nominal power. A combined shut-down and start-up system, sketched in Fig. 7, has been proposed which allows to preheat the feedwater system and the turbines during start-up and to cool down all thick walled components slowly during shut-down. The system consists of a high pressure control valve (α) which takes over the task of pressure control from the turbine valve, followed by a battery of 4x24 separators of 410 mm diameter each and with a total weight of 27.6t, followed by a drain tank to provide hot steam (γ) and liquid (δ) independently to preheat the feedwater tank, the preheaters and the turbines [15]. Excess steam, in particular during the shut-down phase, is supplied to the condensers. The mass flow rate of feedwater is controlled by the speed of the feedwater pump (β) and the feedwater temperature is controlled by the steam extraction valve to the condenser (ε). The system was tested with a numerical APROS simulation and showed to work successfully after some optimization. The feedwater mass flow was kept constant up to 50% thermal power, so that the outlet enthalpy of the reactor was ramped up proportionally to the thermal power. At 50% power, a steam temperature of 500°C was reached and the system could be switched over to the turbines.

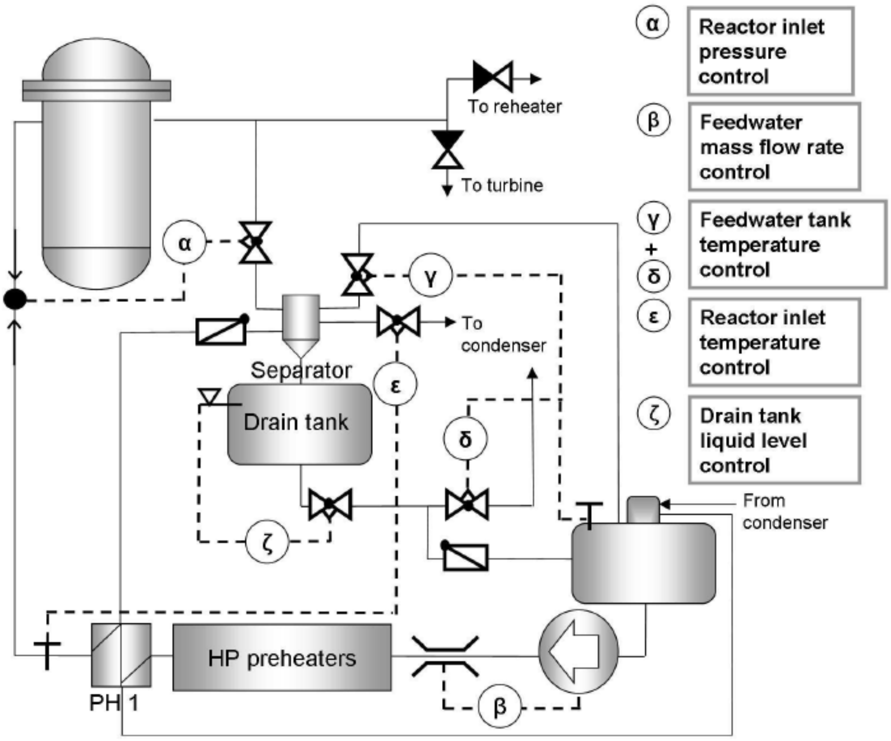

Fig. 7: Control of the combined start-up and shut-down system [18].

An alternative option to start-up and shut-down the reactor under full pressure has been proposed by Oka et al. [1]. They combined the tasks of the separator and of the drain tank in Fig. 7 to a single flash tank. It must be designed large enough to separate steam and liquid such that steam can be extracted from there without droplet entrainment to warm up the turbines. Oka et al. [1] predict a required flash tank height of 7.5 m and an inner diameter of 3.4m for a pressure of 6.9 MPa, resulting in a total weight of 52.3t for a plant size comparable to the HPLWR.

While a sliding pressure operation in the load range must be avoided to exclude dryout in the core, a sliding pressure start-up process with two-phase flow from the core outlet to the separator has been proposed alternatively by Oka et al. [1]. However, such system has not been considered as feasible for the HPLWR concept because of downward flow of coolant in the 1st superheater with the risk of flow reversal of steam.

A further optimization of the start-up system could be to combine the idea of the flash tank with the concept of the separator battery by including cyclones inside the flash tank, such that the tank size can be reduced at given maximum moisture content in the steam line to the turbines. Such optimization will require modelling of two-phase flow in separators which still appears to be a challenge even though such components have already been used since many years in boiling water reactors.

These early design and feasibility studies demonstrate that the start-up system is basically new, even though some similarities with fossil fired power plants can be mentioned. As a consequence, numerical predictions alone cannot yet considered to be reliable, and integral tests are urgently recommended.

6. Conclusions

On a first look, the major components of the steam cycle are indeed quite similar to those of supercritical fossil fired power plants. This includes the turbines, turbine valves, condensers, condensate and feedwater pumps, feedwater tank and preheaters. Quite different components, on the other hand, will be the reheater, as well as the start-up system and its control. A number of detailed analyses will be required to meet the high level expectations of nuclear facilities before such a steam cycle can be licensed. Among the most challenging thermal-hydraulic simulations will be the cooling heat transfer at supercritical pressure in the reheater, the two-phase flow in separators and in the feedwater tank, and the coupled neutronic / thermal-hydraulic simulation of flow in the core during the start-up or shut-down procedure.

Another critical issue which has not been looked at in detail yet is the shielding and protection of activated steam in the turbine building. Here, the long term experience with boiling water reactors can certainly help to find practical solutions.

7. Acknowledgement

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