STEAM GENERATOR CONCEPT OF A SMALL HTR FOR REHEATING AND FOR REMOVAL OF THE RESIDUAL HEAT

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Abstract

The steam generator of a small HTR is arranged above the core in an in line design of the primary loop, thereby helium flows upwards. Water flows downwards in the steam generator to realize cross flow. To achieve stable evaporation conditions during part load operation it is desired to realize upward evaporation in the steam generator. Moreover if the steam generator is also used as a heat sink for removal of residual heat, this desire of upwards evaporation becomes more imperative. It is possible to realize the design of steam generator with upwards evaporation by arranging a hot gas duct in its central region, so that hot helium can flow upwards through it. Therefore helium enters the steam generator from the top and flows downwards and water upwards.

In the presented design, a heat exchanger is arranged in the central region of the steam generator instead of a hot gas duct. Hot helium of 750 °C flows upwards in this heat exchanger and thereby cools down to the temperature of about 700 °C before it enters the bundle of the steam generator at the top. Through an intermediate loop this heat is transfered outside the primary loop, where in an extra heat exchanger live steam is reheated to improve the thermal efficiency of the plant. This intermediate loop works on the basis of forced convection and transfer about 25 MW for reheating.

During the shutdwon operation of the reactor, this heat exchanger in the central region of the steam generator serves as a heat sink for removal of the residual heat through natural convection in the primary loop. At the same time it is further possible, that intermediate loop also works on the basis of natural convection, because during shutdown operation only a very small amount of heat has to be removed and moreover the outside heat exchanger can be arranged much higher above the central heat exchanger to get favourable conditions for the natural convection.

Some fo the highlights of the central heat exchanger are:

- coaxial straight tubes with inner pigtail for transport of the hot intermediate medium
- on the primary helium side baffles are arranged to increase heat transfer coefficient
- this bundle of tubes can be inspected in situ without opening of the primary circuit to improve its reliability.

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1. Introduction

The steam generator of the small HTR industrial reactor is arranged above the core in an inline design of the primary loop and thereby helium flows upwards and water flows downwards to realize a design of crossflow heat exchanger /1/. Therefore only downhill boiling of water is possible. In the side by side version of the primary loop, by which helium flows downwards through the core, a staggered arrangement of the steam generator under the core is necessary to realize upward evaporation of water /2/. The criteria of uphill boiling of water is demanded to achieve stable evaporation conditions during part load operation of the steam generator. This desire becomes more imperative if the steam generator is also used as a heat sink for removal of the residual heat. Also it is possible to realize the concept of a steam generator in an in-line version with upward evaporation by arranging a hot gas duct in the central region of the steam generator, so that hot helium can flow upwards through it. Therefore helium enters the steam generator from the top and flows downwards and water upwards. Similar concept of upward evaporation of water is also possible by arranging the superheater tubes in the central region instead of a hot gas duct and by arranging the rest heating surface of economizer and evaporator in an annulus part of the steam generator around this central region. Thereby helium enters the region of the evaporating tubes also from the top and flows downwards /3/.

In the presented concept an extra heat exchanger for an intermediate loop is arranged in the central region of the steam generator above the core, which is used for reheating of steam and can be further used for removal of the residual heat. Thermohydraulics and design characteristics of this concept are given in the following chapters.

2. Description of the Primary-, Intermediate- and Secondary Loops

The flow sheet of the primary, intermediate and secondary loop is shown in Fig. 1. Helium is heated in the pebble bed core of 250 MW thermal power to the temperature of 750 °C and flows upwards through the core and the heat exchanger arranged in the central region of the steam generator above the core. Thereby it cools down to the temperature of 700 °C and transfers about 25 MW to the intermediate loop, before it enters the steam generator at the top. After reversing its direction helium flows downwards and transfers 225 MW to the secondary loop of feedwater and live steam. At the steam generator outlet helium temperature is 250 °C. After that helium flows upwards in an annulus region between the outer boundary shell of the bundle and the steam generator's shroud, before it enters the two circulators arranged at the top of the pressure vessel. The high pressure helium of about 250 °C flows downwards along the wall of the pressure vessel and thereby builds a cold boundary layer for the whole pressure vessel from the top to the bottom.

For the intermediate loop Nitrogen is selected as a heat transfer medium, which is particularly suited in respect of the safety criteria. Moreover system pressure of the intermediate loop has been selected to be higher than the primary pressure of the helium and has the value of 75 bar, therefore in case of any failure of a tube of the intermediate heat exchanger only Nitrogen can flow in the primary loop. Further the Nitrogen has the favourable characteristic of neutron absorbing and no other chemical reaction with the materials of the reactor is possible, so that such a damage will not cause any hazard to the plant and the surroundings.

Nitrogen at the temperature of 285 °C flows uniformally to all the inlet central tubes from the entrance chambre, gets heated in a cross-counterflow in downward direction to about 320 °C, reverses its direction at the bottom

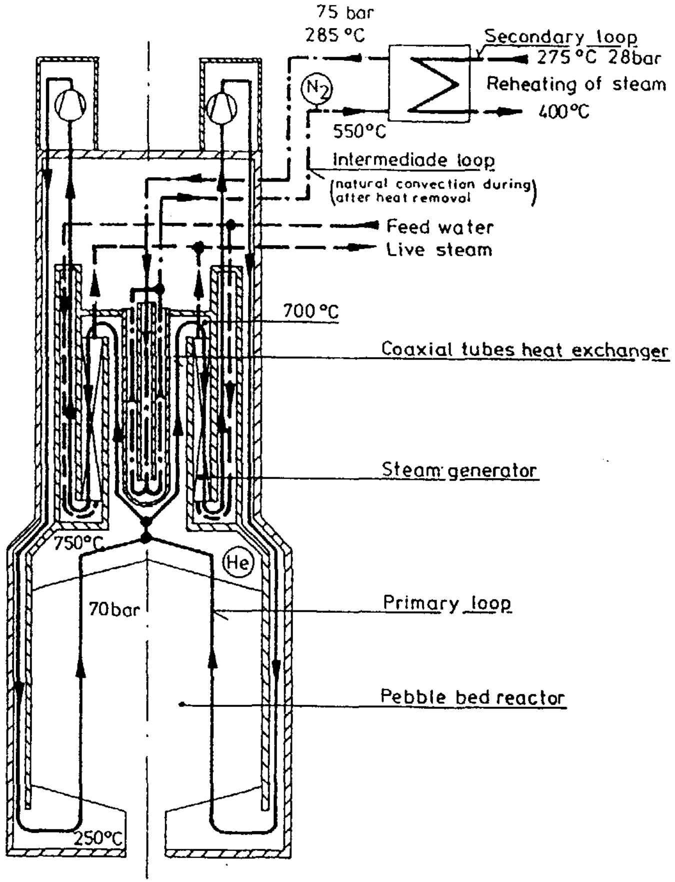

Fig.1: Flow sheet of primary, intermediate and secondary loops

and flows upwards in the annular space of the coaxial tubes. Thereby it gets further heated to the temperature of about 550 °C through hot primary helium. Both mediums flow in parallel in upward direction. At the top Nitrogen enters the exit chamber of the intermediate loop. From here it is transported in two ducts to the bottom of the outer secondary heat exchanger. Nitrogen flows upwards on the shell side of this heat exchanger, cools down to the temperature of about 285 °C and is transported back to the entrance chamber of the primary heat exchanger via two ducts.

At the top of the secondary heat exchanger steam from the high pressure turbine enters the inlet header. The total mass flow of the steam at the pressure of 30 bar and temperature of about 275 °C flows downwards in the tubes of helical tubes bundle and gets heated to the temperature of about 400 °C, enters the outlet header before it is tranported to the medium pressure turbine.

3. Layout of the Primary and the Secondary Heat Exchangers

The primary heat exchanger is arranged directly above the core, so that its reliability during all load conditions has to be guaranteed. Therefore easy maintenance of this heat exchangers should be achievable. This can be realized, because of easy accessability from the top of the pressure vessel and without opening of the primary circuit, the straight tubes of the heating surface can be inspected in situ according to the necessary requirements. Moreover, in case of failure, the possibility of replacement of the damaged tube is given. These safety requirements of easy maintainability and the possibility of replacebility can be fulfiled easily with the design of straight tubes heat exchanger, although their heat transport efficiency is not so good as that of helical tubes.

Further as already mentioned because of Nitrogen as a cooling medium of the intermediate loop, leackage of the tube can be detected and is tolerable because of unsensitiveness of the components of the primary circuit against this medium.

This heat exchanger concept has been selected under the following design aspects:

- The temperature of the helium at the entrance in the steam generator bundle is high enough and will not cause any difficulty by determining the heating surface.
- The dimensions of this heat exchanger allows sufficient freedom in designing the steam generator e.g. inner- and outer diameter, height etc.
- Heat transported through the intermedieate loop is sufficient for the reheating of steam.

Table 1: Main Design Data of the Primary Heat Exchanger

Thermal power	25 MW
Primary loop (Shell-side)	Helium
Massflow	96,25 kg/s
Inlet temperature	750 °C
Outlet temperature	700 °C
System pressure	70 bar
Pressure drop	0,006 bar
Heat transfer coefficient	$925 \frac{W}{m^2 . K}$
Intermediate loop (Tube-side)	Nitrogen
Massflow	90,00 kg/s
Inlet temperature	285 °C
Outlet temperature	550 °C
Temperature at the end of the inlet tubes	320 °C
System pressure	75 bar
Pressure drop: Inlet tubes	0,12 bar
Outlet tubes	0,29 bar
Heat transfer coefficient: Inlet tubes	$1170 \frac{W}{m^2 . K}$
Outlet tubes	$1070 \frac{W}{m^2 . K}$
Bundle data:	
Number of tubes	91
Bundle diameter	1,5 m
Bundle height	10 m
Heating surface	235 m^2
Overall heat transfer coefficient	$400 \frac{W}{m^2 . K}$
Tube geometry: (coaxial)	
Inner diameter of inlet tubes	45 mm
Wall thickness	2,5 mm
Outer diameter of inlet tubes	50 mm
Inner diameter of outlet tubes	70 mm
Wall thickness	6 mm
Tube pitch	125 mm
Material	Incoloy 800 H

- Small pressure drop by the normal operation on the shell- and tube-side gives favourable condition for removal of the residual heat.

The main data of the primary heat exchanger are given in table 1.

Coaxial tubes are selected for the flow of Nitrogen in the heat exchanger bundle, as already used for the steam reformer bundle /4/.

Through the inner tubes Nitrogen flows downwards and gets heated in counter-flow to the upward stream of Nitrogen through the annular space of coaxial tubes. The upward flow of hot helium heats Nitrogen in parallel flow. Through this arrangement of Nitrogen flow, no insulation between inlet and outlet streams of Nitrogen inside the coaxial tubes is necessary. Further in the selected design straight inner tubes have been considered, although some advantages are given if helical tubes would be used. The thermal elongation between the inner and outer tubes can be better compensated and the temperature of the Nitrogen at the bottom of the tubes is higher, which results in lower heat flux between helium and Nitrogen.

The design of the entrance and exit chambers for the intermediate loop of Nitrogen is shown in Fig. 2. At the top of the pressure vessel also the feedwater and live steam headers are arranged. The main design features of the small HTR in an inline version is thereby not changed. Anyhow, detailed construction of the presented design has still to be done.

The main data of the secondary heat exchanger are given in table 2. Live steam flows in the helical tube bundle from the top to the bottom, thereby it gets reheated through the intermediate loop. Nitrogen flows upwards on the shell side. The design of this heat exchanger is based on the steam generator concept.

The main data of the steam generator are given in table 3. The steam generator works on the basis of the once through flow: feedwater from two headers entering a given tube is preheated, evaporated and superheated in the same tube, before it enters the two live steam headers. The heating surface consists of helically coiled tubes, arranged in concentric tube cylinders.

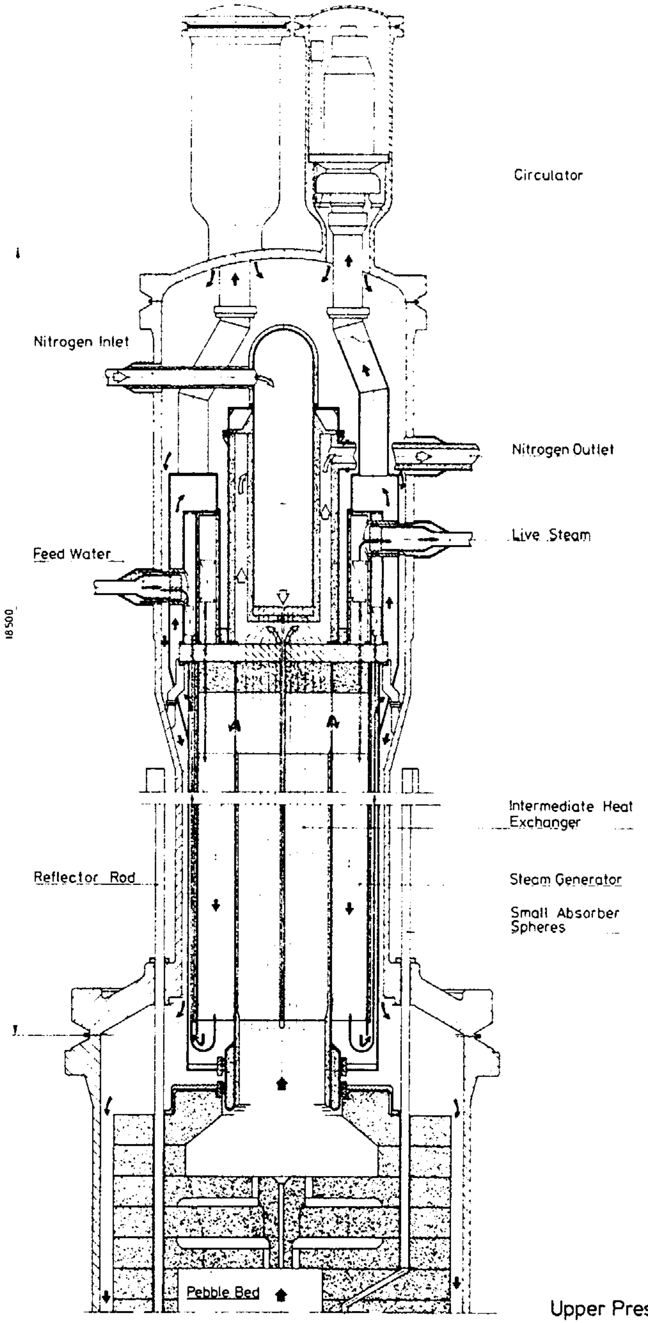

Fig.2

Upper Pressure Vessel with Internals

Table 2: Main Design Data of the Secondary Heat Exchanger

Thermal power	25 MW
Intermediate loop (Shell-side)	Nitrogen
Massflow	90,00 kg/s
Inlet temperature	550 °C
Outlet temperature	285 °C
System pressure	75 bar
Pressure drop	0,14 bar
Heat transfer coefficient	$520 \frac{W}{m^2.K}$
Secondary loop (Tube-side)	Steam
Massflow	86,6 kg/s
Inlet temperature	276 °C
Outlet temperature	400 °C
System pressure	30 bar
Pressure drop	2,9 bar
Heat transfer coefficient	$1520 \frac{W}{m^2.K}$
Bundle data	
Number of tubes	270
Bundle diameter	2,0 m
Bundle height	9,0 m
Heating surface	1410 m^2
Overall heat transfer coefficient	$335 \frac{W}{m^2.K}$
Tube geometry	
Inner diameter	28 mm
Outer diameter	36 mm
Tube pitch (transverse, longitudinal)	47 mm

Table 3: Main Design Data of the Steam Generator

Thermal power	225 MW
Primary loop (Shell-side)	Helium
Massflow	96,25 kg/s
Inlet temperature	700 °C
Outlet temperature	250 °C
System pressure	70 bar
Pressure drop	0,3 bar
Secondary loop (Tube-side)	Water/Steam
Massflow of feedwater	86,6 kg/s
Feedwater conditions	220 bar/180 °C
Live steam conditions	185 bar/535 °C
Bundle data	
Number of tubes	182
Inner diameter of the bundle	1,6 m
Outer diamter of the bundle	2,8 m
Height of the bundle	10,0 m
Heating surface	1880 m^2
Tube dimensions	25 x 4 mm
Tube pitch (transverse, longitudinal)	40 mm

4. Reheating of the Steam

Reheating of the steam in the primary circuit of the high temperature reactor is avoided, because of the penetrations in the pressure vessel and due to the accidents in case of failure of the tubes. Further it is desired, that the secondary pressure of the steam should be higher than the primary system pressure, therefore optimal steam pressure for the reheating cannot be selected.

With intermediate loop with Nitrogen at the higher pressure, some of the objections can be avoided, although penetrations in the pressure vessel are still necessary.

The pressure of the steam for reheating is optimized at the value of 30 bars. On the expansion line of the high pressure steam turbine, steam has a temperature of about 275 °C. The whole mass flow of the steam is reheated through the intermedieate loop till the temperature of about 400 °C, before it enters the medium pressure steam turbine. With this measure of reheating, the plant efficiency can be increased from about 39 % to 40 %. Although this improvement of the plant efficiency is less than the value, which is maximum obtainable, but the design optimization in respect of the arrangement of primary heat exchanger, steam generator and reactor shutdown rods has still to be done.

5. Conditions for the Residual Heat Removal

Helium flows upwards through the core in the normal operation of the primary circuit. After reactor shutdwon, helium still has a tendency to flow upwards due to the natural thermal convection in the core, as long as the primary system pressure is maintained. As the primary heat exchanger is arranged directly above the core, it serves as a heat sink for the upward flowing helium and heat can be transported from the core to the intermediate loop.

The secondary heat exchanger is arranged about 10 m higher than the top of the pressure vessel. Through this arrangement a natural convection of the intermediate loop during the reactor shutdown is possible. Preliminary investigations have shown, that about 10 % of the normal mass flow of Nitrogen flows due to natural convection during shut down conditions. This is possible, because in the normal operation, the total pressure drop of the intermediate loop is about 0,8 bar, and thermal buoyancy of about 0,05 bar is given. In this way it is possible to remove about 1 % of the thermal power of the core, which is equivalent to the residual heat production about 20 minutes after reactor shutdown.

A separate cooling water loop cools the secondary heat exchanger during reactor shutdown period.

6. Conclusions

The presented design of the intermediate loop for a small HTR allows reheating of the steam and at the same time it serves also for removal of the residual heat with natural convection after reactor shutdown. Further uphill evaporation of water in steam generator is possible with this design. Extra expenditure for designing this loop can be compensated through the improved plant efficiency. Moreover a very reliable system for removal of residual heat is possible.

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