Proceedings of the 4th International Topical Meeting on High Temperature Reactor Technology
HTR2008
September 28-October 1, 2008, Washington, DC, USA

HTR2008-58146

STATE OF THE ART OF HELIUM HEAT EXCHANGER DEVELOPMENT FOR FUTURE HTR-PROJECTS

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ABSTRACT

In Germany two HTR nuclear power plants had been built and operated, the AVR-15 and the THTR-300. Also various projects for different purposes in a large power range had been developed. The AVR-15, an experimental reactor with a power output of 15 MWel was operated for more than 20 years with excellent results. The THTR-300 was designed as a prototype demonstration plant with 300 MWel and should be the technological basis for the entire future reactor line. The THTR-300 was prematurely shut down and decommissioned because of political reasons. But because of the accompanying comprehensive R&D program and the operation time of about 5 years, the technology was proved and essential operational results were gained.

The AVR steam generator was installed above the reactor core. The six THTR heat exchangers were arranged circularly around the reactor core. Both heat exchanger systems have been operated successfully and furthermore acted as a residual heat removal system.

The technology knowledge and experience gained on these existing HTR plants is still available at Westinghouse Electric Germany GmbH since Westinghouse is one of the legal successors of the former German HTR companies. As a follow-up project of THTR, the HTR-500 was developed and designed up to the manufacturing stage. For this plant additionally to the 8 steam generators, two residual heat removal heat exchangers were foreseen. These were to be installed in a ring around the reactor core. All these HTRs were designed for the generation of electricity using a steam cycle. Extensive research work has also been done for advanced applications of HTR technology e.g. using a direct cycle within the HHT project or generating process heat within the framework of the PNP project.

Because of the critical attitude of the German government to the nuclear power in the past 20 years in Germany there was only a very limited interest in the further development of the HTR technology. As a consequence of the German decision, at the beginning of the 90s, to phase out nuclear power completely, research and funding of further development of HTR reactor design was also cut down. Today's HTR reactor designs, such as the PBMR in South Africa, use a direct cycle with a gas turbine. This technology is also based on the THTR technology and PBMR is a licensed party. For the HTR-PM in China and the future oil sand projects powered by HTR's in Canada and Siberia however the use of steam generators is required.

Westinghouse and Dresden University cooperate in the field of steam generator technology for HTR reactors. The existing know-how for HTR is based on a huge pool of knowledge gained by the past German HTR projects mentioned above and consists especially of the design methodology, the mechanical layout and material issues for helium heated steam generators. The project team consists of experienced specialists who have worked on HTR projects in the past and of young graduate engineers. Main goal of the project is to analyze the existing know-how and to adjust it to the state of the art. As a first step, the existing design and its methodology is being analyzed and the different points of improvement are identified. The final step of the program is the description of a new methodology

which fulfills the severe requirements of the customer and all of the actual licensing conditions. One of the reasons why this project has been launched is that the requirements of life expectancy for HTR components increase and the material limits will be reached, especially at high temperatures. This implies that the design of helix heat exchangers has to allow in-service inspections; this was not a requirement for the previous THTR design. Methodologies for in-service inspections already had been developed, but they are not sufficient for today's tube lengths and have to be adapted. Another example, based on operating experience, is using reheaters to increase the efficiency is not recommended today. Using supercritical steam conditions to increase the efficiency should be investigated instead. In general, the economic benefit has to be balanced against the additional costs resulting from better material and more complex manufacturing.

INTRODUCTION

In Germany, two High Temperature Reactors were developed, designed, constructed, commissioned and operated successfully. The AVR (Arbeits-gemeinschaft Versuchsreaktor) was built by BBK (Brown Boveri/Krupp Reaktorbau GmbH) in 1961 and served as a research reactor. The goal was to demonstrate the feasibility of the physical principle and to prove the inherent safety features and it also served as a test rig for HTR fuel elements. Its design outlet temperature was 850 °C but it was also operated at an outlet temperature of 950 °C since 1974 to demonstrate the feasibility of producing process heat. Thus the AVR already has been a VHTR. The thermal power of 46 MW was transferred by one involute tube-type heat exchanger which was positioned above the reactor core. The electrical power was 15 MW. The AVR was operated successfully for more than 20 years.

The THTR (Thorium High Temperature Reactor) was built in 1971 by BBC/HRB (Brown, Boveri & Cie AG/ Hochtemperatur-Reaktorbau GmbH) as a follow-up project of the AVR and served as a HTR prototype. The THTR core outlet temperature was 750 degrees Celsius. The thermal power of 750 MWth was transferred to the secondary circuit by six helical tube type heat exchangers which were in an annular arrangement around the reactor core. The electrical power was 308 MW. The THTR was operated for 5 years and then shut down and decommissioned for political reasons. Its technology is the basis for all our future HTR plants independent of applications.

Due to mainly political reasons the funding of nuclear research by the government for HTR reactor concepts has been reduced considerably since the THTR has been stopped. Several years ago South Africa and China started designing small power plants in the range of 200-400 MWth on the basis of proven German technology. The South Africans decided to go for a direct cycle. The Chinese HTR-PM concept is based on the HTR-10 technology with a steam generator. The HTR-PM consists of two reactor modules, each of 250 MWth, connected to a single steam turbine. As mentioned before, steam generators are also needed for other innovative applications of the HTR, e.g. the oil sand projects in Canada and Siberia.

Westinghouse Electric Germany GmbH is one of the legal successors of the former German HTR companies and it maintains the accumulated knowledge and experience of this technology. Together with Dresden University, Westinghouse launched an engineering project in the area of high temperature reactor technology to collect the existing know-how of the design methodology, the mechanical layout and the materials for helium heated steam generators. This brought together a team of experienced engineers and young graduates to update the existing German database to the state of the art. The design methodology has also to be updated to current rules and guidelines. As a first step, the existing design methodology has to be analyzed and the different points of improvement have to be identified. With respect to the steam generators the existing technology from the THTR and HTR-500 has also to be reviewed in great detail.

AVR STEAM GENERATOR

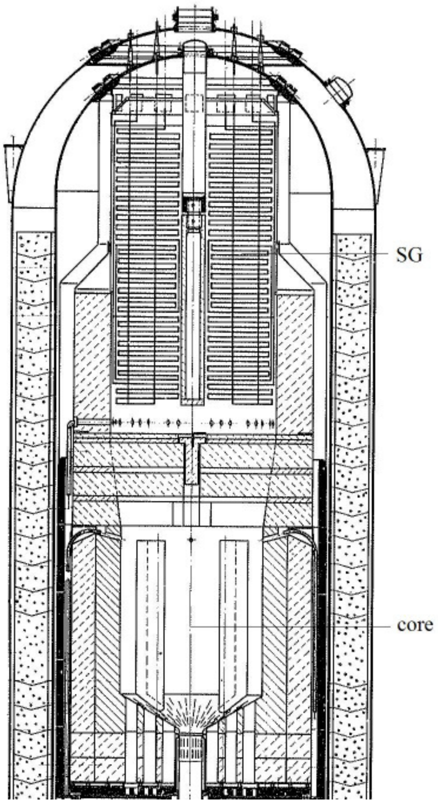

Figure 1 AVR Steam Generator and reactor core [1]

Figure 1 shows the AVR Steam Generator which was positioned above the reactor core. Following the primary circuit, first the helium flows through the reactor core from the bottom to the top and then through the heat exchanger also from the bottom to the top. The reactor was designed for an outlet temperature of 850°C, but it was also operated at a temperature of 950°C since 1974. The helium outlet temperature of the steam generator is 275 °C. The heat is transferred in a cross current flow principle from the primary to the secondary circuit. The cold helium at the top of the heat exchanger is then recirculated to the reactor core entrance.

Figure 2 shows the AVR steam generator. It is an involute tube type heat exchanger which is separated in four parallel systems. Each system consists of a feedwater inlet header, tube system, superheated steam cooler and superheat steam outlet header. The steam generator was build by several layers of involute bended tubes, which were connected by semicircular tubes at the inner diameter. Figure 2 shows the principle. The fluid enters the bold type involute tube A at point 1. Reaching point 2 it makes a u-turn and flows back to point 3. There it makes a vertical u-turn one layer up or down and flows through tube B in a similar way than before. This flow pattern is resistant to temperature distortion of the primary circuit due to a maximized utilization of the profile.

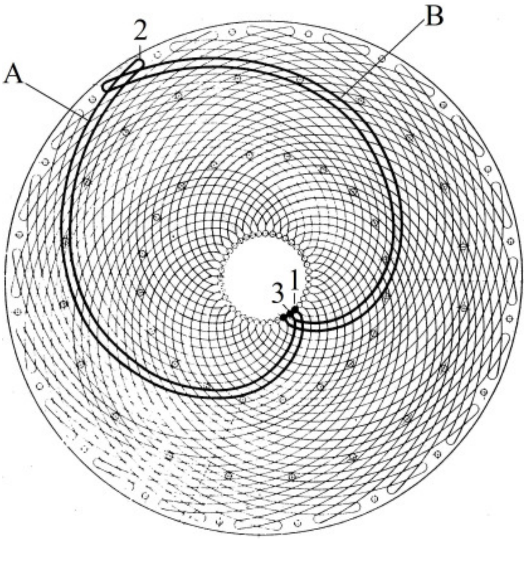

Figure 2 Involute tubes [2]

Figure 3 shows a picture of the AVR Steam generator which was taken during the manufacturing. Various circularly arranged vertical pipes transport the fluid to the respective heat transfer section and connect the superheated steam cooler to the superheater. These tubes also fix the involute tubes and stabilize the construction. Due to an elaborate tube system an upward evaporation is achieved. For example the semicircular tubes at the outer diameter of the steam generator are necessary to link the different sections within the economizer, evaporator and superheater.

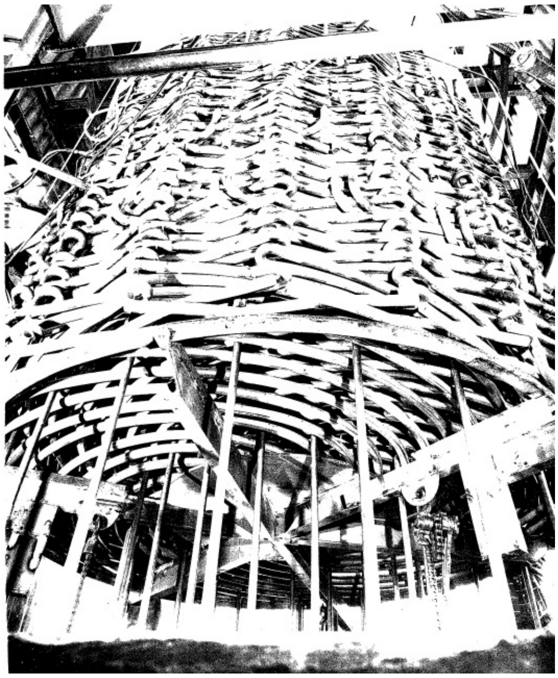

Figure 3, involute tubes [2]

THTR STEAM GENERATOR

The six THTR steam generators were arranged in an annular manner around the reactor core. Additionally to its primary purpose the steam generators served as a residual heat removal system. Figure 4 shows the top view.

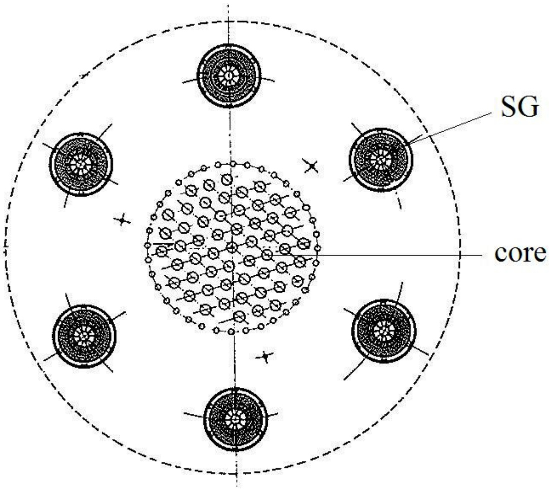

Figure 4 THTR top view [3]

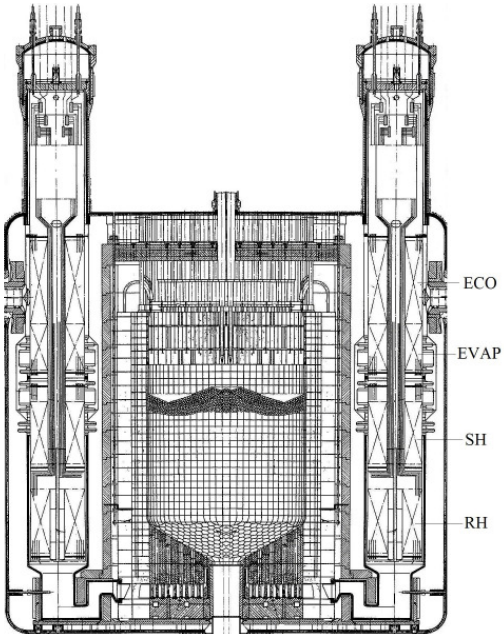

Figure 5 THTR reactor core and steam generators [3]

Figure 5 shows the cross section. The cold helium enters the reactor core at the top and leaves at the bottom. The heated helium passes through various channels in the pebble bed to the bottom of the steam generators. The flow direction within the steam generators is from the bottom to the top. On the way it passes the helix type tubes of reheater (RH), superheater (SH), evaporator (EVAP) and economizer (ECO). At the top of the steam generator the helium flow enters the steam generator annulus by a u-turn, flows through the blower and then outside the liner to the bottom of the steam generator. There it enters the bottom of the reactor annulus and flows outside the graphite reflector to the top where it enters the core region again.

Figure 6 shows a picture of the THTR steam generator which was taken during manufacture. It shows the inner core barrel and the helical type tubes which are coiled around it. Superheater, evaporator and economizer consist of fifteen cylindrical layers of tubes which always are coiled in the opposite direction to the next layer of tubes. The reheater consists of fourteen layers and is constructed using the same principle.

The steam is generated by the hot helium using following basic principles.

- Counter-current- flow in the economizer, evaporator and superheater follow the.

- Parallel-flow in the reheater.

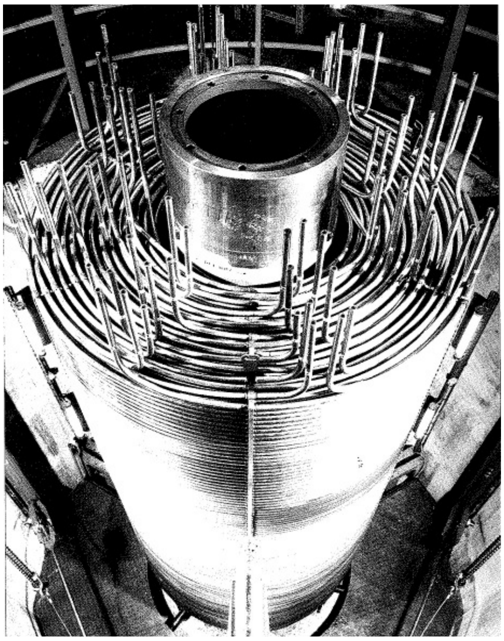

Figure 6 helical tubes [4]

The feed water inlet is at the top of the steam generator. The water is preheated in the economizer and flows downwards into the evaporator where it evaporates. The steam flows downwards through the superheater and at the outlet the flow direction turns by 180 degree. Inside of the core barrel it flows through straight tubes to the outlet of the heat exchanger at its top. From there the steam is led to the turbine. Low pressure steam after expansion through the turbine reenters the top of the heat exchanger and flows downwards through straight tubes inside the core barrel. At the bottom the steam flow makes a u-turn and flows parallel with the helium through the reheater. Passing the reheater outlet the steam again flows through straight tubes inside of the core barrel to the heat exchanger outlet at the top of the steam generator.

HTR-500 STEAM GENERATOR

Due to the operating experience of the THTR the HTR 500 steam generator was improved and simplified but is has no reheater. The HTR-500 steam generator is a helix tube type heat exchanger which consists of economizer, evaporator and superheater. It uses an integrated tube sheet for feed water and steam with a single pipe penetration through the vessel cover. This allows a full and easy access for in-service inspections; the expansion zone was also simplified. Additionally to the 8 steam generators two residual heat removal (HR) heat exchangers were installed in circular manner around the reactor core. Figure 7 shows the top view of the HTR-500.

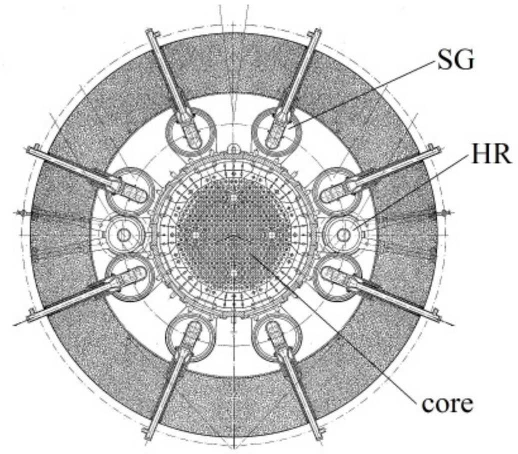

Figure 7 HTR-500 top view [5]

The hot helium flows horizontally to the bottom of the steam generator, where it flows vertically to the top. There the cold helium makes a u-turn and flows outside the steam generator back from the top to the bottom. There it flows back into the reactor core.

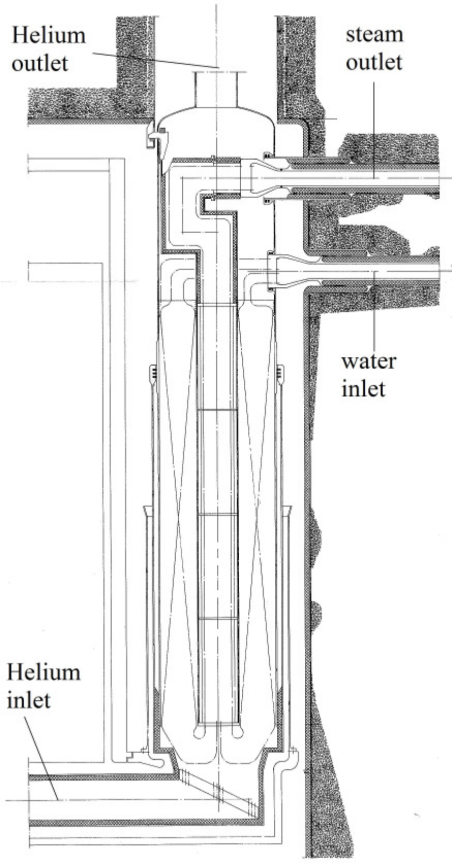

Figure 8 HTR-500 steam generator [5]

Figure 8 shows the HTR-500 steam generator. The distinct simplified extensible zone to compensate for thermal expansion is at the top of the steam generator. The u-shaped tubes form the steam outlet. Also the feed water inlet is at the top of the steam generator. The water flows through the helix tubes from the top to the bottom, where it evaporates. At the bottom of the steam generator the superheated steam makes a u-turn and flows through the core barrel to the top.

The HTR-500 steam generator design has no reheater and thereby avoids complicated and expensive tube connection systems. Simplified and safe technology combined with a high availability is more important than a higher degree of efficiency associated with higher capital cost. The HTR-500 steam generator also allows in-service inspections without opening the primary circuit. All heat exchanger tubes are guided through tube sheets at the water inlet and steam outlet which allow easy access.

MATERIALS & MANUFACTURING

Table 1 shows the used materials for AVR, THTR and HTR-500 steam generator tubes. With the experience gained with the AVR and THTR steam generators an evolution towards more appropriate materials is seen.

For the first HTR design, the AVR the steam generator economizer was built of unalloyed normalized steel. Evaporator and superheater were made of two different low alloyed steels. For the next HTR generation, the THTR economizer, evaporator and parts of the superheater were made of two different low alloyed steels and the other parts of the superheater as well as the reheater were made of high-alloyed solution annealed steel. The HTR-500 design employs similar materials as used for the THTR.

The interaction of Ni and Fe-Ni base alloys with the reactive impurities H_2O, CO, H_2 and CH_4 in the helium of the primary circuit of the HTR causes corrosion effects that can significantly influence the mechanical properties. Depending on gas composition, gas supply rate and temperature, carburization or decarburization can occur[6].

The manufacturing and assembling of the steam generator is being done in several parallel steps. The THTR and HTR-500 steam generators consist of several helical bundles. For manufacturing the tubes have been bent and threaded into several base plates to fix them.

Table 1 Materials

	AVR		THTR		HTR-500	
Eco	economizer 1	St 35 8 G3	economizer 1	15 Mo 3	economizer	15 Mo 3
	economizer 2	St 35 8 G3	economizer 2	15 Mo 3		
			economizer 3	10 Cr Mo 9 10		
Evap	final evaporator	15 Mo 3	evaporator	10 Cr Mo 9 10	evaporator	10 Cr Mo 9 10
	evaporator	15 Mo 3				
	pre-evaporator	15 Mo 3				
SH	pre-superheater	15 Mo 3	superheater 1	10 Cr Mo 9 10	superheater 1	10 Cr Mo 9 10
	superheater	10 Cr Mo 9 10	superheater 2	10 Cr Mo 9 10	superheater 2	X 10 Ni Cr Al Ti 3220 *
			superheater 3	X 10 Ni Cr Al Ti 3220 *		
			superheater 4	X 10 Ni Cr Al Ti 3220 *		
			superheater 5	X 10 Ni Cr Al Ti 3220 *		
RH			reheater	X 10 Ni Cr Al Ti 3220 *		

* solution annealed

CALCULATION AND MODELING

The computer program DERZ for the thermal calculation of steam generators and reheaters for various primary fluids was established during the work on the Fast Breeder Project[7]. It was made flexible enough to be applicable to all steam generation systems relevant to nuclear power plants. The code is used to determine the characteristic thermodynamic and geometric design parameters of heat transfer or cooling circuits. It can be used for helix tube type, u-tube type or straight tube bundle heat exchangers. The heat exchanging fluids can flow in parallel-flow, counter flow, crossing parallel-flow or crossing counter flow wise. The primary fluids can vary from sodium to helium or carbon dioxide to steam.

The computer program module DESIRE was designed for transient calculations of steam generators. It can be integrated into DSNP (Dynamic Simulator for Nuclear Power-Plants) and is as flexible as DERZ concerning steam generator types.

COMPARISON

Table 2 shows the most significant values for comparison of the steam generators of the AVR, the THTR and the HTR-500. This is necessary to evaluate the development of HTR steam generators. The principal difference of AVR and THTR/HTR-500 steam generators is the temperature profile of the water/steam circuit. The involute type tubes of AVR generate a uniform temperature profile whereas the helix type tubes of THTR and HTR-500 can cause differences of temperature inside different tubes. To ensure a uniform outlet steam temperature, various throttle orifices have to be adjusted.

Due to the past operating experience and economic considerations, it is evident that using reheaters is no longer required for the optimization of efficiency. The considerable cost for the large number of connecting tubes does not pay off compared to the gain in efficiency.

Table 2 Comparison of AVR and THTR Steam Generators

	unit	AVR	THTR-300	HTR-500
Reactor				
Thermal Power	(MWth)	46	760	1264
Power Capacity	(MWel)	15	308	500
Net Generation	(GWh)	1.63	2.756	-
Built	(-)	1961	1971	-
First Criticality	(-)	1966	1983	-
Net Synchronisation	(-)	1967	1985	-
Commissioning	(-)	1967	1987	-
End of Operation	(-)	1988	1988	-
Decommissioning	(-)	1988	1989	-
Operating Time	(years)	21	5	-
Steam Generator				
Thermal Power/ Heat Exchanger	(MWth)	46	128	160
Heat Surface Type	(-)	involute	helix	helix
Number of Heat Exchangers	(-)	1	6	8
Geometry				
Height	(mm)	5535	18574	12300
Diameter	(mm)	3550	2055	2960
Heat Exchanger Volume	(m^3)	53.27	22.175	84.64
Overall Weight of Tube Bank	(t)	46	65	
Heating Surface	(m^2)	1762	983.2	1055
High Pressure				
Height	(mm)	5535	8280	7000
Outer Diameter	(mm)	3550	1970	2454
Inner Diameter	(mm)	590	815	820
Heating Surface	(m^2)	1762	923.5	1045
Reheater				
Height	(mm)	-	500	-
Outer Diameter	(mm)	-	1970	-
Inner Diameter	(mm)	-	738	-
Inner Heating Surface	(m^2)	-	59.7	-
Inlet Temperature	(°C)	-	365	-
Inlet Pressure	(bar)	-	55	-
Outlet Temperature	(°C)	-	535	-
Outlet Pressure	(bar)	-	49	-
Helium				
Cooling-gas Inlet Temperature	(°C)	850	750	1390
Cooling-gas Outlet Temperature	(°C)	275	250	260
Gas Throughput	(kg/s)	17	49,4	70
Mean Effective Pressure	(bar)	10.8	38.49	49
Pressure Drop	(bar)	0.0088	0.44	0.3
Steam				
Feed Water Temperature	(°C)	115	180	190
Feed Water Pressure	(bar)	116.7	240	
Main Steam Temperature	(°C)	505	550	530
Main Steam Temperature (after water injection)	(°C)	-	535	-
Main Steam Pressure	(bar)	74	186.2	190
Steam Quantity	(t/h)	56	154.8	228.6

IN-SERVICE INSPECTIONS

Higher requirements in the life expectancy imply higher material requirements. This in turn means improved detection systems for the material aging processes. Thus, the design of heat exchangers has to allow in-service inspections which were previously not a requirement for the THTR. Although these in-service inspections methods have already been developed, they are not sufficient for today’s tube lengths. Another problem for the in-service inspections is that the inner diameter of the high pressure tubes varies for the THTR steam generator from 15 mm of the superheater to 19.8 mm of the economizer. This makes it difficult to do automated in-service inspections. For further development, such as for the HTR-500, these aspects have to be considered.

FURTHER IMPROVEMENTS

Using supercritical steam conditions in order to increase the efficiency should be investigated. Conventional coal-fired power plants such as the BoA (Braunkohlekraftwerk mit optimierter Anlagentechnik) achieve efficiencies higher than 43 %. In general, the economic benefit has to be balanced against the additional costs e.g. for materials and manufacturing.

CONCLUSION

The operational experience gained with AVR and THTR already has been implemented in the further development for HTR-500. The next step of the current project is to analyze this know-how in a very detailed manner followed by an analysis of critical points in order to upgrade the methodologies to the state of the art. Also supercritical steam conditions should be investigated as a design feature to increase efficiency.

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