GTHTR300C FOR HYDROGEN COGENERATION

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ABSTRACT: The newly proposed system concept of GTHTR300C for hydrogen cogeneration is aligned with technologies already under development in JAERI. The system is based on a high temperature gas cooled reactor (HTGR) and co-produces electricity by a direct gas turbine cycle and hydrogen by a thermochemical iodine-sulfur (IS) process cycle. JAERI has been actively developing the technologies of the reactor and two production cycles, and extensive experience and database have been accumulated to date. As a result, the early demonstration of the system is expected at minimum cost and risk of development.

The GTHTR300C employs a maximum unit power of 600MW for a passively safe HTGR, and selects 950^{o}C reactor outlet coolant temperature. An intermediate heat exchanger (IHX) is located between the reactor pressure vessel (RPV) and the gas turbine system. The heat capacity of IHX is 170MW and is transferred efficiently in 950-850oC temperature range to hydrogen generation. The balance of the reactor thermal power is used for electric generation of gas turbine at a turbine inlet temperature of 850^{o}C. The share of cogeneration of hydrogen to electricity meets the projected demand of both markets during 2020-2030 when the first plants are to be deployed.

Through employment of the gas turbine and IS process cycles, the cogeneration efficiencies in the range of 45-50% are expected. The cogeneration also reduces the number of standardized components that would have been necessary to produce electricity and hydrogen in separate systems. This fact is reflected in the design of a unified reactor and the elimination of a separate primary coolant circulation system for process heat generation.

The design advantages of system simplification, high performance, reliance on available technologies, and demand-oriented market introduction support competitively economical prospect of the GTHTR300C.

This paper describes the original design features focusing on the plant layout and plant cycle of the GTHTR300C. The present development status of the plant technologies including the HTTR with IHX, the GTHTR300 system, and the IS process are presented. The advantages of the GTHTR300C are discussed in greater detail.

KEYWORD : HTGR, HTTR, Gas Turbine, Intermediate Heat Exchanger, Hydrogen Production

0. INTORDUCTION

Development of a highly efficient electric generation system by the helium gas turbine with HTGR is underway in JAERI[1]. The gas turbine development program includes a basic design of the GTHTR300 and R&D for key technologies of the gas turbine system. In parallel, development of the hydrogen production system by the IS process method is has been conducted[2]. The IS process method with HTGR is an ultimate clean hydrogen production system without CO_2 emission and is highly expected as the future energy system in 2030s. On the other hand, successful operations of the HTTR have been carried out since 2002 to accumulate various operational data for future HTGRs[3]. The HTTR is a Japan's first HTGR with its thermal power of 30MW and outlet temperature of 950^{o}C.

However, design investigation of a HTGR taking into advantage of the technological basis obtained in the above mentioned research programs has never carried out. The GTHTR300C was designed based on these technological developments to supply clean and economical energy source and to prevent environmental disruption such as global warming and following freak draught, overflooding etc. The GTHTR300C generates electricity by similar scale gas turbine system with that of the GTHTR300 and produces hydrogen by the IS process method. It will meet the demand for both electricity and hydrogen in 2030s. The efficiency of the electric generation is approximately 46% and is enough to compete against existing electric generation systems and future systems. The amount of hydrogen production is 1.9 ton/hour with the efficiency of 45.5 %.

The most important design consideration for the GTHTR300C is to use the technologies accumulated in JAERI so that the technology development for this system shall be limited and the investment risk is minimize. However, it is also considered that the system is technically feasible and economically supreme as the new energy source in 2030s.

The research program on the GTHTR300 was entrusted from Ministry of Education Culture, Sports, Science and Technology.

1. DEPLOYMENT OF GTHTR300C

The GTHTR300C was designed in compliance with the same design philosophy of the GTHTR300, SECO (Simplicity, Economical Competitiveness and Originality). Greatly simplified design was adopted to avoid plant complexity and to minimize any significant technical development. Also, this system is economically competitive against the other systems. Existing technologies developed for HTTR, to be developed for the GTHTR300 and the IS process method for hydrogen production are used. Most of them have Japanese originality. The followings are the present status for each development.

1.1 GTHTR300 development [1]

Figure 1 shows the conceptual view of the GTHTR300, and Table 1 compares the major specifications of the GTHTR300 and GTHTR300C. The GTHTR300 is a helium cooled, graphite moderated, prismatic core HTGR with 850^o outlet helium gas temperature and 600MW thermal power. The outlet temperature was determined as a trade-off of thermal efficiency and system complexity. For example, turbine blade cooling is not necessary in the case of outlet temperature of 850^o. Avoidance of sophisticated blade forced cooling greatly reduces risk of turbine malfunction and increases reliability,which is judged more important than having efficiency maximized during commercial launch. Thermal power of 600MW was determined in order to limit fuel temperature below 1600^{o}C even in the worst accident that no forced cooling is expected. The gas turbine unit is horizontally located in the rector building, and the heat exchanger unit and the gas turbine unit are separately installed in the Power Conversion Vessel (PCV) and Heat Exchanger Vessel (HEX) respectively. Due to the unique system arrangement, maintenance is made easy because the gas turbine and heat exchangers may be simultaneously serviced without interference.

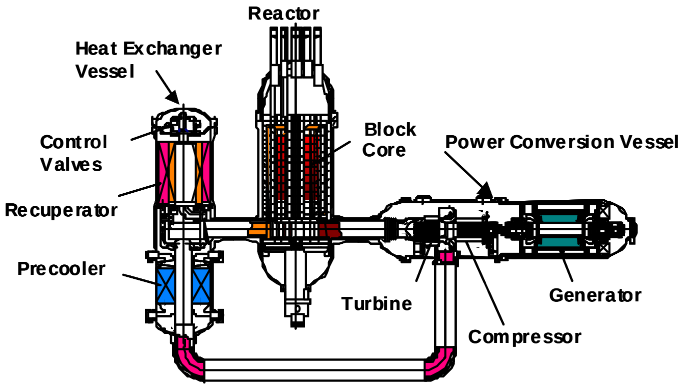

FIGURE 1 Conceptual view of GTHTR300

TABLE 1: Comparison of plant specifications between GTHTR300 and GTHTR300C

	GTHTR300 power plant	GTHTR300C H_2 cogeneration plant
Reactor thermal power	600 MWt/module	600 MWt/module
Reactor pressure vessel	SA533 (Mn-Mo) steel	SA533 (Mn-Mo) steel
Reactor core coolant	Helium gas	Helium gas
Core coolant flow	439 / 403 kg/s	324 kg/s
Core inlet temperature	587 / 663^{o}C	594^{o}C
Core outlet temperature	850 / 950^{o}C	950^{o}C
Core coolant pressure	6.9 MPa	5.1 MPa
Core power density	5.8 W/cc	5.8 W/cc
Average fuel burnup	120 GWd/ton	120 GWd/ton
Refueling interval	24 / 18 months	18 months
GT conversion cycle	non-intercooled direct Brayton cycle	non-intercooled direct Brayton cycle
GT cycle pressure ratio	2.0	2.0
Power conversion efficiency	45 / 50%	45.7%
Electricity production	274 / 300 MWe	202 MWe
H_2 conversion process		thermochemical (e.g. S/I) or hybrid (thermal-electro)
H_2 conversion efficiency	-	45~55%
H_2 Production	-	1.9~2.4 ton/hr
Total plant efficiency (net)	45~50%	45~48%

The reactor core design is based on that of the HTTR so as to reduce R&D needs for the new system.

The pin-in-block type fuel blocks are stacked annularly in the core. Accordingly, fuel design and fabrication technology are almost the same as that of the HTTR except that the buffer thickness between the coating layers is now increased to improve retaining capacity of fission products in higher burnup necessary commercial fuel cycles.

The first basic design phase including safety evaluation and economical assessment will finish at end of FY-2003. During this design phase, Check & Review (C&R) by a special board consisting of members from utilities, universities, industries and the other national research laboratories has been organized every six months so that the design can meet the requirement from private sectors. The final C&R on the first basic design phase will be conducted in 2004 and technical suggestions from this committee will be reflected in the second basic design phase to be carried out from FY-2004 to FY-2007.

In addition to the basic design, the development of the compressor and magnetic bearing for the gas turbine system started in FY-2001. The development aims to address the uncertainties remaining still in these key components, namely aerodynamics in the compressor and control performance of the magnetic bearing. In the compressor development, 1/3 scale compressor with four stages was fabricated and the test is currently underway. In the magnetic bearing development, 1/3 scale rotor with simulated weights of turbocompressor and generator will be manufactured, and the magnetic bearing performance will be confirmed. The tests will finish at the end of FY-2007. A control and operational performance test using 1/3 scale turbocompressor system is also planned. A helium turbine gas with an electric heater capacity of about 5 MW will be constructed and the control and operational performance of the system will be confirmed.

1.2 IS process method development [2]

The IS process method has been studied since 1970s and General Atomics (GA) performed the most intensive work. In Europe and in Japan, several variations of the process have been studied which differed in the mode of reaction and methods to separate reaction products. Efforts on the process chemistry have been concentrated on how to separate the hydrogen iodide and sulfuric acid produced in the Bunsen reaction and on how to carry out the hydrogen iodide processing to produce hydrogen. Flowsheeting studies have been carried out and it was reported that thermal efficiency in the range of 40-50% might be possible when utilizing intensive and efficient heat recovery networks [4-6].

Researchers at JAERI have been working to demonstrate the continuous hydrogen production using an IS process variant featuring the liquid-liquid phase separation. Stable and continuous hydrogen evolution was successfully carried out with the rate of 1 liter hydrogen (STP) per hour by an integrated operation of the basic reactions and products separations using a glass-made apparatus [7].

Based on the know-how accumulated in the experiments, a scaled-up glass apparatus was constructed with nominal hydrogen production rate of 50 liter per hour. Its basic flowsheet is the same with the former one, except that it is equipped with newly devised pumps and sensors for monitoring process parameters such as flow rates and liquid levels. These modifications enable the continuous hydrogen production test under efficient process conditions.

In parallel with the hydrogen production test, selection of materials of construction for large-scale plant is another important issue of the process development, because very corrosive chemicals such as iodine and sulfuric acid shall be handled. Corrosion tests have been carried out in the typical process environments using commercially available materials.

The above-mentioned study is scheduled to complete in FY 2004. After its completion, JAERI is planning to proceed to the bench-scale study that includes following subjects: (1) development of the components such as reactors, separators, pumps and piping, which are made of selected materials of construction, to be used in the design and fabrication of the pilot plant, (2) study on chemistry and technology required for the plant operation under high pressurized conditions, (3) development of the simulation codes and acquisition of supplemental physico-chemical data required for the process simulation.

1.3 IHX development

The IHX for the HTTR is rated at 10MW and is a helically coiled He/He type in which the primary coolant flow passes the shell-side and secondary flow inside the tubes. Figure 2 shows the HTTR-IHX. JAERI had developed a Ni-base super alloy Hastelly XR as the heat transfer tube and a tube bundle material. Besides the material development, JAERI developed a welding method between Hatelloy XR and low alloy steel, high temperature resistance structures absorbing thermal expansion difference between high and low temperature helium gas, insulation structure etc. Furthermore, JAERI proposed a structural standard and evaluation method for the high temperature structures consisting of Hastelloy XR[8]. So far, the structural integrity and thermal performance in 850C condition were confirmed in the power-up test of the HTTR. The structural integrity and thermal performance in 950C condition will be tested in 2004.

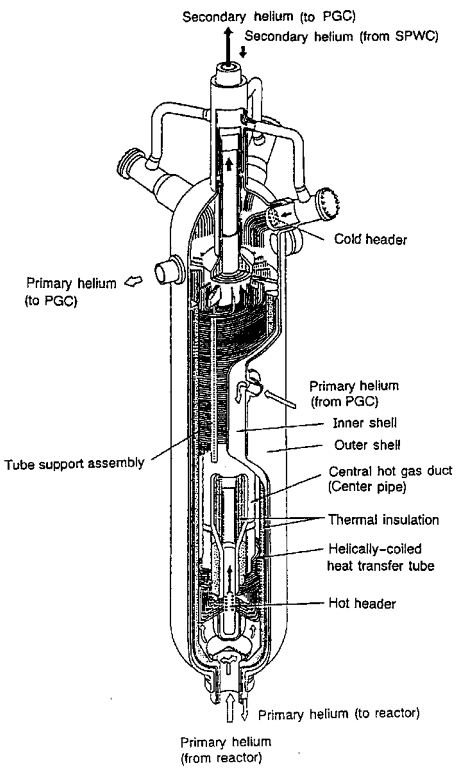

FIGURE 2 IHX of HTTR

2. DESIGN DESCRIPTION OF GTHTR300C

2.1 Plant layout and GT design

Figure 3 shows the system layout of the GTHTR300C. The helically coiled He/He IHX is installed between the RPV and the gas turbine system. Even though the thermal capacity for the gas turbine system decreases to 430MW from 600MW for the GTHTR300, no major design change of the primary components was made except the addition of the IHX. A comparison of major design specifications between GTHTR300 and GTHTR300C was shown earlier in Table 1.

Figure 4 shows the cycle process scheme of the GTHTR300C. The reactor power is 600MWth and its outlet coolant gas temperature is 950^{o}C. Of the total reactor thermal power, about 170MWth is used for the process heat and the balance for the gas turbine system. The reactor heat is transferred via the IHX to a secondary helium loop and then through a compact heat exchanger to the third loop of hydrogen production system. The reactor outlet helium gas of 950^{o}C enters the shell side of the IHX and exits it at 850^{o}C. The helium gas of 850^{o}C from the IHX drives the turbine and goes to the recuperator, precooler and compressor. The outlet helium gas of 135^{o}C from the compressor is guided to cool the RPV to allow for the vessel made of the pressure vessel steel used in existing LWR. The plant generates approximately 200MWe of electricity.

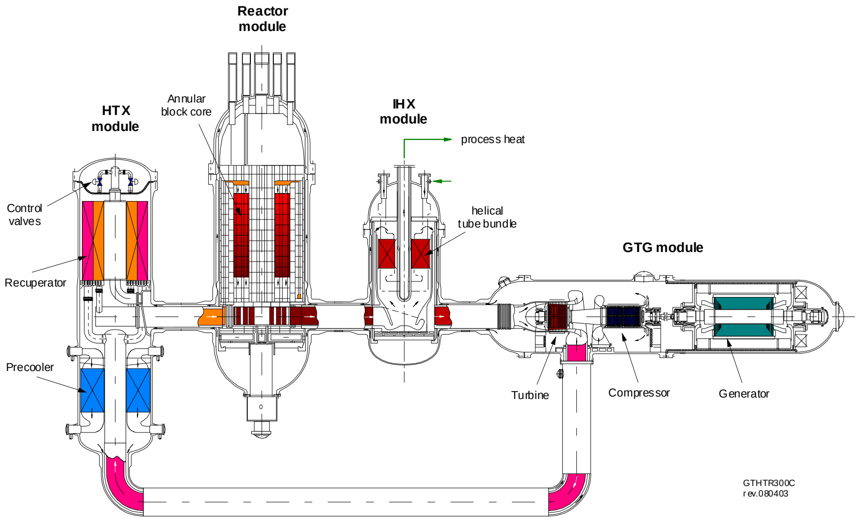

FIGURE 3 System layout of GTHTR300C

Only IHX of a compact surface geometry, such as plate type, were previously thought to be economically viable for IHX. This would be correct if a small drop in temperature, say 50^{o}C, were presumed across the IHX. In the case of the GTHTR300C, however, the LMTD (logarithmic mean temperature difference) of the IHX is about 150^{o}C, made possible by the particular location of IHX installation where primary heat is transferred to secondary loop in a high, narrow temperature range of 950-850^{o}C. Because LMTD is inversely proportional to surface area required, a compact IHX unit is obtained of helical tube-and-shell construction in the present system.

Since settling primary coolant pressure is no longer governed by desire to down-size a primary gas circulator, which is not needed in GTHTR300C, the primary coolant pressure is lowered to about 5MPa from 7MPa of the power-only reactor for the following two design needs. The first is to reduce the total pressure difference imposed on heat exchangers between reactor and hydrogen loops so that the lifetime of the heat exchangers (IHX and process heat exchangers) can be greatly extended. The second need is to maintain design and performance of the gas turbine system similar to that of the GTHTR300. As a result, the gas turbine system is made common in both design and performance to both the GTHTR300 and GTHTR300C. Although the lower primary pressure increases specific cost of gas turbine equipment, the cost saving in heat exchangers and primary circulator in addition to the pressure vessels mitigates economic penalty to overall system.

Since power output is rated lower, the weight and length of the electric generator rotor is proportionally reduced from those of the GTHTR300 generator, making the rotor considerably stiffened and reducing the number of critical speeds in rotational speed range. The technical uncertainty for the magnetic bearing suspension of this system will be cleared once the ongoing magnetic bearing R&D for the GTHTR300 is to be completed. Also, no technical problem is foreseen for the compressor and turbine after completion of present compressor and turbine development for the GTHTR300.

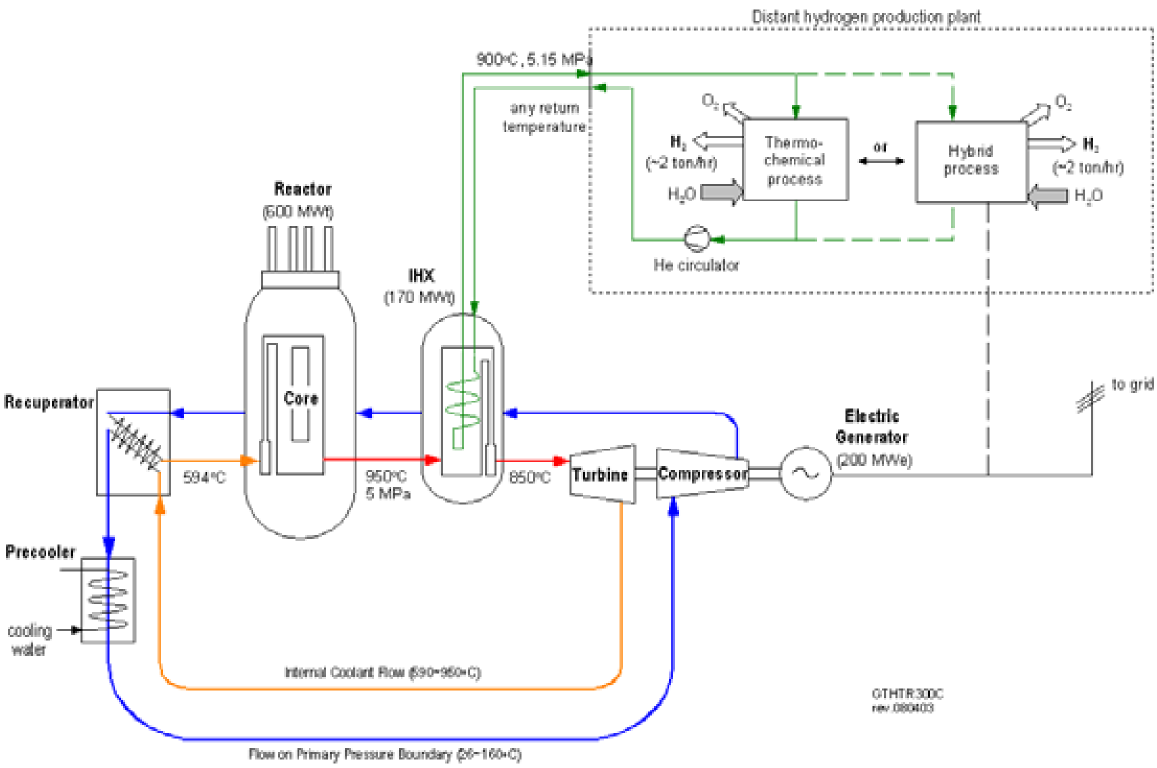

FIGURE 4 GTHTR300C power and hydrogen cogeneration cycle scheme

2.2 Reactor core design

The maximum fuel temperature during the rated operation shall be lower than 1400C to reduce fission product release from the fuel during the long-term operation. Because of fission product plate-out on the surface of the primary components, it is not easy to access to the gas turbine system for maintenance. In the GTHTR300, the maximum fuel temperature during the rated operation is about 1400C and it occurs at the beginning of the operation[9]. In order to meet the requirement from utilities such as two-year continuous operation, the initial enrichment of the GTHTR300 is 14wt%. The control rod is inserted to compensate the excess reactivity at the beginning of the core. That skews the reactor power profile and makes the power density peak as high as about 13-15W/m^3. In the GTHTR300C, the continuous operational period is reduced to 1.5 years. In addition to the change of the operational condition, the cooling performance of the fuel was enhanced by reducing the outer diameter of the fuel pin and by increasing the coolant flowrate around the fuel with the high peaking factor. The combination of requirement and design change keeps the maximum fuel temperature in the GTHTR300C almost 1400^{o}C despite the outlet temperature increases to 950^{o}C. Therefore, the existing coated fuel particle made of SiC is available for the system.

2.3 IHX structural design

Table 2 makes a comparison of the major specifications between HTTR-IHX and GTHTR300C-IHX. Haxtelloy XR is used for heat transfer tubes and tube bundles in both designs. Identical tube size is also used in the two designs so that the experience gained in design, fabrication, and operations of the HTTR-IHX is directly applicable to the GTHTR300C-IHX. To achieve acceptable IHX design life, it is essential that the creep damage of the high temperature structures be kept as low as possible. The heat transfer tube is exposed to 950^{o}C helium gas. In this high temperature range, the creep strength is quite low. Therefore, unless the pressure between the primary and secondary helium gas is essentially balanced, the creep damage of the heat transfer tube due to the pressure load becomes high

TABLE 2 Comparison between IHX for HTTR and IHX for GTHTR300C

	Unit	HTTR IHX	GTHTR300 Cogen IHX
Design Type	–	He/He helical tube and shell	He/He helicol tube and shell
Thermal Rating	MWt	10	168
LMTD	^{o}C	113	154
Heat transfer area	m^2	244	972
Shell side flow			
Flow rate	kg/s	3.4	323.8
Temperature (inlet/outlet)	^{o}C	950 / 389	950 / 850
inlet pressure	MPa	4.060	5.020
pressure loss	MPa	0.001	0.003
Tube side flow			
Flow rate	kg/s	3.0	81.0
Temperature (inlet/outlet)	^{o}C	237 / 869	500 /900
inlet pressure	MPa	4.210	5.150
pressure loss	MPa	0.020	0.066
Tubing			
Type	–	bare tube	bare tube
Material	–	Hastelloy-XR	Hastelloy-XR
Tube sizing (O.D. x t)	mm	31.75 x 3.5	31.75 x 3.5
Tube effective length	m	22	12
Tube bundle			
Bundle diameter (I.D. x O.D.)	m	0.827 / 1.297	1.056 x 4.278
Effective height	m	4.87	2.55
Number of tubes	–	96	1000
Number of coiled columns	–	6	30
Tube pitch (traverse/longitudinal)	mm	47 / 47	56 x 56
Effective bundle weight	ton	6	30
Pressure vessel			
Steel	–	2 $^1/_4$ Cr - 1Mo	SA533 (Mn-Mo)
Outer diameter	m	1.90	4.89

and quickly exceeds the limit of 1.0. In the GTHTR300C-IHX, the pressure difference is kept lower than 0.015MPa by a differential pressure control system to limit the creep damage. The same pressure control system of the HTTR is used for the GTHTR300C. In the HTTR design experience, it was found that the creep damage was accumulated mainly in the startup and shutdown condition when the primary stress due to the pressure difference is kept low by the pressure control system. In the startup and shutdown condition, the secondary stress becomes high due to the temperature change in both primary and secondary side and relaxes due to the accumulation of the creep deformation. In the HTTR, the number of the startup and shutdown is more than 200 times in 20 years of life time to conduct various test operations. However, the number of startup and shutdown would be about 1/5 of the HTTR in commercial reactors such as the GTHTR300C. A lifetime of 40–60 years is achievable for the GTHTR300C-IHX.

3. ADVANTAGES OF GTHTR300C

3.1 Meeting the goals of hydrogen economy

By combining power generation and substantial production of hydrogen in an efficient commercial cogeneration plant, the GTHTR300C will provide cost-competitive, CO_2 emission-free electricity for traditional energy consumption while meeting significant demand for hydrogen as transportation fuel.

3.2. Simplifying R&D

The system takes advantage of the existing technologies or technologies under present development.

3.2.1 Gas turbine system

Advanced technologies for the helium gas compressor and gas turbine, magnetic bearing are the key to this system. The R&D program for the GTHTR300 includes the 1/3 scale compressor model test and 1/3 scale magnetic bearing development. The key technology will be developed in this R&D program for the GTHTR300. Development for the gas turbine system is not necessary for the GTHTR300C. The design advantage of the GTHTR300 gas turbine system such as the horizontal turbomachine layout, the conventional steel RPV, the highly efficient recuperator and so on are directly applicable to this system.

3.2.2 IHX

The same design philosophy of the IHX in the HTTR is applied for that in the GTHTR300C. Also, the same material, welding method, structure are used for the IHX. Design conditions of this system such as temperature, pressure difference between the primary and secondary helium gas are almost the same as those of the HTTR. For example, the pressure difference between the primary and secondary helium gas is controlled as low as 0.015MPa to keep the creep damage of the heat transfer tube as low as possible. Due to this design philosophy, no significant development is necessary for the GHTR300C-IHX in this system. Existing technologies are available.

3.2.3 Reactor core

The reactor technology for this system is based on the technology developed for the HTTR. The pin-in block type prismatic core is used for the reactor core. An advanced coated fuel particle such as ZrC is not indispensable for this system. Accumulation of performance data for the high burnup fuel is necessary for the system.

3.2.4 Primary and secondary circulator

Large-scale helium gas circulators shall be placed in the primary circuit unless the gas turbine is not installed. The maximum size of the helium gas circulator with a gas bearing is not applicable for the 600MWth reactor. It is in the current state of technology that the size of the HTTR circulator is near the maximum. In the HTTR, three main circulators are operated in parallel to provide the total core coolant circulation necessary. As the total flow rate of the 30 MW HTTR is 12.2 kg/s or 4.0 kg/s for each circulator, a sum of 80 gas circulators would have been needed for the total flow of a 600 MWth reactor or very large-size circulator with a magnetic bearing must be used. However, design manufacturing and operational experience for this type and size of circulator has never been obtained.

In the secondary circuit, a helium gas circulator with an oil or water bearings can be used because potential water or oil ingress into the secondary circuit does not damage the system significantly.

3.2.5 IS process

The hydrogen production system by the IS process method is installed in the third loop in the system. The malfunction of the hydrogen production system does not impair the continuous operation of the reactor to generate power.

4. R&D NEEDS FOR GTHTR300C

By sharing technologies of the HTTR and GTHTR300, additional development needs for the GTHTR300C are reduced to the following:

1. Compact heat exchanger in secondary loop

Development of a compact heat exchanger in the secondary circuit is necessary. The design requirement is relatively low and many design options are available based on future technology developments in a conventional system because it does not comprise the primary boundary. However, it still needs R&D for material development and performance demonstration.

2. System performance demonstration

The GTHTR300C, which is meant for commercial unit, shall demonstrate its ability to operate in normal cogeneration mode or with electric or hydrogen system operating alone in such a case as forced shutdown of either system. The results of the system performance analysis showed that the reactor could be continuously operated with the above variable load conditions. However, an actual demonstration test is warranted for performance confirmation.

5. CONCLUSION

The GTHTR300C incorporates a block type modular HTGR, rated at 600MWth and 950^{o}C outlet coolant temperature, and employs a Brayton-cycle gas turbine for electricity generation and an IS process method for hydrogen production. The system can be deployable around 2020. It has the following advantages as a future cogeneration HTGR:

- The system meets the future demand for hydrogen and electric generation.
- The technology developed for the HTTR, to be developed for the GTHTR300 and thermochemical IS process method is directly applicable to this system. Therefore, additional development is not high and commercial deployment can be pursued at low risk by entwining with advanced development of HTTR and GTHTR300.
- New developments for large primary capacity helium circulator, primary IHX are not necessary. This enables nearer term and lower cost of deployment for this system.

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