FAPIG-HTGR Plant Concept of Low Cost and Small Power

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FAPIG (THE FIRST ATOMIC POWER INDUSTRY GROUP) has started the feasibility study of commercial plant, FAPIG-HTGR. The concept aims at low construction cost, small electric power and sufficient inherent safety considering the reduction of investment cost and risk, and alleviation of siting problem. The goal of the concept is (1) electric power of 100MW/module, (2) construction cost of 1200$/kWe and (3) no evacuation in hypothetical accident without reactor containment vessel. Direct gas-turbine cycle is adopted and core inlet/outlet temperature of 500°C/900°C is selected, which enables thermal efficiency of 46% and thermal power becomes 220MW. Mn-Mo steel is employed as RPV material. The goal will be achieved based on the design philosophy of extreme system simplification and power increase in the range system simplification is not deteriorated. The simplification of reactor system is realized by primarily two region fuel loading scheme and the RCCS improved with fins. The simplification of power conversion system and the feasibility of downsizing by high-speed rotation are under consideration. The investigation of further cost reduction by further system simplification and cost estimation are scheduled in next stage. Highly hypothetical accident including reactivity is also scheduled to analyze in next stage.

KEYWORDS: HTGR, pebble bed core, gas turbine, FAPIG, small and medium sized reactor, advanced reactor

I. Introduction

The flexibility of a plant power, the reduction of investment cost and investment risk as well as the improvement of economical efficiency is requested to the future nuclear power plant under the recent circumstances of the slowdown and the uncertainty increase of electricity demand growth. Moreover the simple and easy-to-understand safety concept for the public is required.

The small modular high temperature gas-cooled reactors (HTGRs) that have superior inherent safety characteristics can meet these requirements. Many development programs of the commercial small modular HTGR plant with gas turbine such as PBMR in South Africa, GT-MHR of USA/Russia with the cooperation of French/Japanese private companies are now undertaken in the world.

Responding to these social needs, Fuji Electric Co., Ltd. is developing pebble bed small modular HTGR plant (FAPIG-HTGR) together with other members of FAPIG, aiming at the improvement of a plant power flexibility and safety margin. The electric power of a module is about 100MW and the electric power of a standard plant is about 400MW with four modules.

The preliminary design concept of FAPIG-HTGR is described in this paper.

II. Design Goal of FAPIG-HTGR Plant

The design goals of FAPIG-HTGR plant are as follows based on the above-mentioned market needs.
(1) The electric power per module is about 100MW.
(2) Construction cost per kWe is lower than 1200$/kWe to be competitive to large advanced LWRs.
(3) The sheltering and evacuation of the public is not necessary even in hypothetical accident without leak tight reactor containment vessel.

III. Basic Design Philosophy

1. The Common Design Philosophy of Small Modular HTGRs

Small modular HTGR power plants such as PBMR, GT-MHR, GTHTR300 etc. overcome the demerit of small scale by the following means.
(1) By adopting closed cycle direct gas turbine system and increasing the inlet/outlet temperature of a reactor, the thermal cycle efficiency largely surpasses that of the steam cycle and the secondary system is eliminated.
(2) By utilizing the inherent safety of small modular reactors, the number of safety class systems is largely reduced and limited compared to LWR.
(3) Based on the inherent safety of small modular reactor, sufficient safety characteristics are retained without the reactor containment vessel.
(4) Being comprised of a few modules, a plant can flexibly respond to the utility requirement of a plant capacity.
(5) By manufacturing standardized small modules in series, the construction costs are reduced and by expanding the range of manufacturing in factory, site works and construction period are reduced.

2. The Specific Design Philosophy of FAPIG-HTGR

In addition to the above philosophy, the simplification of
the plant systems is given the top priority in FAPIG-HTGR and the power of a module is increased as far as the plant simplification is not deteriorated. Namely extreme simplification such as reduction of components comprising a plant, removal of nuclear grade components and relaxation of requiring functions reduce costs and increase reliability.

Major features of FAPIG-HTGR are summarized as follows.

(1) Three vessel system with no large piping
(2) No active reactor pressure vessel (RPV) cooling system
(3) Simple reactor internal structures
(4) Enhanced inherent safety features
(5) Superior maintenanceability

IV Basic Design

1. Characteristics of the system

   Followings are the characteristics of FAPIG HTGR. The vertical cross section of the reactor system is shown in Fig. 1. Basic specifications are shown in Table 1 for our preliminary study.

   (1) Pebble Bed Core

   The pebble bed core has been adopted to our plant concept due to the bellow reasons;
   - It has lower fuel temperature than the prismatic core in normal operation.
   - It has larger safety margin for the control rod withdrawn or ejection accident due to its less excess reactivity.
   - It has high potential to achieve high plant availability due to continuous fuel exchange in operation.

   (2) Thermal Efficiency and Core Inlet/Outlet Temperature

   The closed cycle direct gas turbine system can attain high thermal efficiency. The thermal efficiency becomes higher when the inlet and outlet coolant temperatures of the core are raised. However the temperature of reactor structures, such as RPV, have to be limited in order to satisfy the criteria under accident conditions. The inlet/outlet temperatures of the core are settled preliminarily to 500/900ºC respectively, and can obtain approximately 46% of thermal efficiency.

   (3) Reactor Power

   The electrical output power of 100 MW is selected to achieve the target construction cost. The thermal power is about 220 MW.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Major specifications for preliminary study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>Value</td>
</tr>
<tr>
<td>Thermal output</td>
<td>220 MW</td>
</tr>
<tr>
<td>Electric output</td>
<td>100 MW</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>46 %</td>
</tr>
<tr>
<td>Core inlet/outlet temperature</td>
<td>500 / 900ºC</td>
</tr>
<tr>
<td>Pressure of primary system</td>
<td>6 MPa</td>
</tr>
<tr>
<td>Core diameter / height</td>
<td>3 / 11 m</td>
</tr>
<tr>
<td>Flow rate of primary system</td>
<td>106 kg/s</td>
</tr>
<tr>
<td>Average power density</td>
<td>2.6 MW/m³</td>
</tr>
<tr>
<td>Burnup</td>
<td>80,000 MWd/t</td>
</tr>
</tbody>
</table>

(4) Fuel loading scheme

   In the multi-pass fuel loading on the pebble bed core, a fuel sphere is loaded to the core many times to get the target burnup. We have adopted “two region loading”, that the fresher fuels, which have larger thermal power, are loaded to the outer region of the core, and the aged fuels, which have lower power, are loaded to the center region. The two region loading can give lower temperature under depressurization accident that restricts core thermal power.

(5) RCCS and Decay Heat Removal System

   The reactor cavity cooling system (RCCS) is installed around the RPV to decrease RPV temperature and to remove decay heat under accident conditions. To achieve superior safety, RCCS removes the heat passively with natural convection of atmospheric air. Even in loss of all power accident, it can remove the decay heat properly and keep RPV temperature within the design limit. Therefore, this plant concept has no active safety cooling system and no emergency generator system of the safety grade.

   The heat resistant steel, such as Cr-Mo steels, for RPV increases the construction cost more than conventional material that is used in the light water reactors (LWRs). We have adopted the same material as LWR’s with enhanced RCCS with finned surface. It can give 10% larger form factor for radiation heat transfer.

(6) The Structure around RPV Lower Head Preventing from Temperature Rising

   (a) The direct contact of high core inlet temperature is avoided by the shroud structures that consist of the core barrel, the shroud of core floor and the cross duct shroud.

   (b) The temperature of RPV is held under its criterion with the indirect cooling system such as RCCS in both normal
operation and accident.

(c) The load on the shroud under the rapid depressurization accident is reduced with the small bores penetrating the shroud. In the depressurization accident, the pressure difference between inside and outside of the core barrel becomes larger and brings severer stress to the core barrel and other structures. The HTR-Module has a pressure balance system to prevent the stress from exceeding admissible one. We install small vent holes on the core bottom structure to keep the same pressures between inside and outside of the core barrel.

(7) Standpipes

The standpipes for control rods and small absorber systems are installed at the top of RPV to maintain their internal structures without opening the closure head of the RPV. The control rod drive mechanism and small absorber system are fastened to the structure above the core barrel, therefore, the control rod ejection accident has not to be postulated.

2. Preliminary Evaluation for the Reactor System

The analyses were performed in order to confirm that the reactor system concept could be feasible by showing the safety criteria are satisfied.

(1) Core Power Distribution in Normal Operation

Nuclear and thermal analyses were carried out for the equilibrium core in normal operation with VSOP code\(^2\). In this calculation model, the two regions have the same volumes. Fig. 2 shows the power density profile. Power density in outer region of the core is larger due to the two region loading. This power distribution is used in the analysis described in the next section (2). The Fuel temperature distribution is shown in Fig. 3 under the full power operation. The maximum temperature is below 1000\(^\circ\)C at the outer region.

![Fig. 2 Core power distribution](image)

(2) Temperature under the Depressurization Accident

The depressurization accident was analyzed with FIDAP\(^2\) which is computational fluid dynamics program using the finite element method. The natural convections inside RPV and between RPV and RCCS are calculated in addition to thermal conduction and radiation. Fig. 4 shows the calculation results of transient temperature in the nominal condition. Taking account of the uncertainties, the temperature satisfies the safety criteria that the fuel temperature is below 1600\(^\circ\)C and RPV temperature is below 427\(^\circ\)C in the accident condition. This results show that the design target of the reactor power 100MWe is achieved using the same RPV material as LWR.

![Fig. 3 Fuel temperature distribution in normal operation](image)

![Fig. 4 Fuel and RPV temperature in the depressurization accident.](image)

3. Power Conversion System

Simplification concepts on the power conversion system are described below.

(1) Simplification by Containing Power Conversion System into One Vessel

Vessel system is simplified to three vessels, RPV, cross-vessel and power conversion vessel, which reduces the volume of the reactor building and improves safety and reliability by removing the large pipes among vessels.

(2) Mass Reduction of Gas Turbine System Adopting High-Speed System
The gas turbine system becomes larger with commercial circulation speed (ex. 3600rpm) and increases the cost and the mass. The mass increase makes the design of bearings difficult. One of the solutions to the problem is the high-speed (ex. 7200rpm), single shaft rotor system. The high speed reduces the stage number of turbine and compressor, makes the system compact and reduces the bearing design load. It also enables the startup of the system by generator rotation with motor mode and easy prevention of over speed by bypass valve control.

The adoption of high-speed system was considered to be impossible in the past because the frequency converter of large power is very expensive. However the recent progress in the technology, especially of IGBT (Insulated Gate Bipolar Transistor) and inverter system, which Fuji Electric has been developing instead of thyristor system, has increased the possibility of low cost frequency converter.

Fuji Electric is exploring the feasibility of the frequency converter and generator with large power to actualize the high-speed gas turbine system.

Gas turbine system such as power turbine, compressors, bearings, heat exchanger etc. is studying at Kawasaki Heavy Industries. The thermal efficiency of about 46% is achieved in preliminary conceptual design stage.

The other solution to commercial speed gas turbine system is multi-shaft system consisting of commercial speed turbine and high-speed compressors drove by other turbines for compressors. However this method is considered not to be able to achieve high efficiency due to the coolant leaks through seals. Also gas jet pump is necessary to start up the system and prevention of turbine over speed is difficult because the turbine shaft is separated from compressors.

V. Conclusions

Fuji Electric and The First Atomic Power Industry Group are undertaking the development of small modular HTGR, FAPIG-HTGR, aiming at the improvement of economic efficiency, flexibility to plant capacity demand, reduction of investment cost/risk and simple and easy-to-understand safety. FAPIG-HTGR concept of 100MWe was constructed with the design philosophy that simplifies plant systems and increases power per module within the range simplification design is not deteriorated.

One of the serious concerns for the cost reduction of small modular HTGR is the removal of reactor containment. It is very difficult to make the public and authorities understand because the difference between this concept and the regulation of LWR is quite large.

Small modular HTGR has inherent safety characteristics. According to the preliminary safety study on FAPIG-HTGR, much possibility of no sheltering or no evacuation of the public has been achieved even in the highly hypothetical accident case combining three events, those are depressurized accident, a control rod withdrawal from the core and reactor scram failure, by retaining the integrity of almost all the fuel due to the inherent safety.

Considering the sufficient safety mentioned above, the simple and easy-to-understand safety for the public, will be accomplished. Inherent safety of small modular reactor has been verified by the safety tests on German experimental HTGR, AVR and is going to be verified by the safety tests on HTTR of JAERI and HTR-10 in China. The simple and easy-to-understand safety and the verification of the inherent safety features by operating reactors will establish the basis of the removal of the leak-tight reactor containment vessel.

In next stage, highly hypothetical accident described above is going to be studied and be assured by analyses. The investigation of further cost reduction by further system simplification and cost estimation of the plant are also going to be done.

Reference