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Project Report

Coupling of Modular High-Temperature Gas-Cooled Reactor with Supercritical Rankine Cycle

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This paper presents investigations on the possible combination of modular high-temperature gas-cooled reactor (MHTGR) technology with the supercritical (SC) steam turbine technology and the prospective deployments of the MHTGR SC power plant. Energy conversion efficiency of steam turbine cycle can be improved by increasing the main steam pressure and temperature. Investigations on SC water reactor (SCWR) reveal that the development of SCWR power plants still needs further research and development. The MHTGR SC plant coupling the existing technologies of current MHTGR module design with operation experiences of SC FPP will achieve high cycle efficiency in addition to its inherent safety. The standard once-reheat SC steam turbine cycle and the once-reheat steam cycle with life-steam have been studied and corresponding parameters were computed. Efficiencies of thermodynamic processes of MHTGR SC plants were analyzed, while comparisons were made between an MHTGR SC plant and a designed advanced passive PWR - AP1000. It was shown that the net plant efficiency of an MHTGR SC plant can reach 45% or above, 30% higher than that of AP1000 (35% net efficiency). Furthermore, an MHTGR SC plant has higher environmental competitiveness without emission of greenhouse gases and other pollutants.

1. INTRODUCTION

China has experienced an annual economic growth of 7–10% over the past two decades and is expected to maintain such growing trend in the following decades. The continuing increase of economic activities needs more and more energy consumption. Following the United States, China has become the second largest energy consumer, accounting for nearly 10% of the world's annual consumption. The major source of energy supply in China is coal, about two-thirds of total primary energy usage. Energy supply by burning large quantities of coal has resulted in serious environmental problems. In addition, overdependence on fossil energy threatens the sustainable supply of energy resources, results in transportation problems, and causes China to confront the security of energy supply. Nuclear energy seems to be one of the solutions to meet energy demand as well as to curb the increasing air pollution and emission of greenhouse gases. This nuclear-generated electricity is safe, clean, and economical and does not emit greenhouse gases. In the past decades, NPPs have played a substantial role in the supply of electricity and produced about 17% of the world's electricity. However, China's NPP produced electricity is just 2.1 percent by 2005 [1]. Continued and expanded reliance on nuclear energy is one key to meet increasing demand for electricity in China and is called for in the National Energy Policy. An ambitious nuclear power plan has been approved by the Chinese government, which presents a total NPPs' capacity of 40 GWe by 2020 [2].

Most of the existing NPPs can be classified into Gen-II. To modify their characteristics of economy, safety, reliability, and flexibility, the Gen-III nuclear systems were developed. EPR, AP1000, and ABWR are ready to assume overwhelming dominance of the Gen-III. However, these systems still have some weaknesses, which did not hamper their success: their thermal efficiency is mediocre; they make rather poor use of fertile materials; their excellent safety relies on sophisticated systems—and sophisticated operators. To delineate the features of the proposed Gen-IV reactors and make them possible, the Gen-IV International Forum (GIF) made efforts to identify the required R&D. Six innovative conceptual reactors were considered to be the most promising among the 100 initially considered. The very high-temperature gas-cooled reactor (VHTR), which is based on the technology of MHTGR with its inherent safety and high-temperature heat supply capability, has been taken as one type of the six concepts [3]. If nuclear energy is to help to significantly reduce greenhouse gases emissions, then generating hydrogen in addition to electricity might prove very valuable and could make the VHTR quite attractive. Another type of the Gen-IV innovative reactors is the supercritical water-cooled reactor (SCWR) system. SCWR is characterized as low-flow rate, high enthalpy increase, and single-phase water-cooling, by which high thermal efficiency and simplified once-through direct steam cycle system is achieved [4]. The Gen-IV innovative reactors can offer significant advances toward sustainability, economics, safety and reliability, proliferation resistance, and physical protection. Though many engineers and scientific researchers have made effort to develop Gen-IV reactors and achieved fruitful advances [3, 5–9], there still exist lots of challenges to face in the thermal and mechanical design. We have to wait for a long time, maybe after 2030.

One of the most promising high-performance NPPs, which can be deployed within a reasonable time frame, is the MHTGR SC steam cycle plant coupling the MHTGR technology and the SC steam turbine technology. The design of MHTGR SC plant should be based on the existing technologies of current MHTGR design and operation experiences of SC FPP. MHTGR can serve as a high quality "Boiler" providing an exit temperature of above 950°C, without emission of greenhouse gases and other pollutants. Furthermore, the MHTGR uses a closed first loop and has the potential to achieve higher efficiency than an SC FPP with the same steam turbine cycle, without heat loss through the stack and power consumption by exhaust gas cleaning facility and by coal preparation. For these reasons, the role of MHTGR SC system has been emphasized on economic electricity generation for near-term nuclear market. Schulenberg et al. [10] made comparisons between Rankine and Brayton cycles and gave conceptual discussions on MHTGR SC plants.

This paper first reviews the MHTGR technologies in Section 2. The current development of SC steam turbine technologies is briefly described in Section 3. Prospective deployments and matching patterns of MHTGR SC plants are discussed in Section 4. Conceptual designs of MHTGR-250 SC plants coupling standard once-reheat steam cycle and life-steam reheat cycle are presented, respectively. Efficiencies of thermal process are defined and calculated for investigations of MHTGR SC plant. A brief conclusion is given in Section 5.

2. DEVELOPMENT OF MHTGR TECHNOLOGIES

2.1. Description on MHTGR

(1) From HTGR to MHTGR

During the last half century, HTGR development has followed an evolutionary process of four general stages and has been subjected to many significant changes from the initial Dragon plant to the present MHTGR.

Stage 1 is the early HTGR research based on gas-cooled reactors (GCRs). HTGR utilizes ceramic fuel particles surrounded by coatings and dispersed in a graphite matrix, along with graphite moderator and helium coolant to permit very high core outlet coolant temperatures. Either prismatic type graphite moderator blocks (block type reactor) or spherical fuel elements (pebble bed type reactor) can be employed.

Stage 2 is the development of HTGR prototype plants including Dragon, Peach Bottom, and AVR. These plants were generally quite successful in achieving high core outlet temperature up to 950°C and validating the UO2 kernel TRISO-coated fuel particle. Such type of fuel represents the foundation for the safety and environmental aspects of the HTGR.

The next milestones in HTGR were the commissions of demonstration plants including FSV and THTR-300. These plants were developed primarily to demonstrate the commercial capabilities of the HTGR as the forerunners to achieve marketability of the large follow-on plant designs. These plants were valuable in demonstrating the attributes of the HTGR, including the TRISO—coated fuel particle.

Stage 4 is the development of MHTGR steam cycle plant. MHTGR concept originated in Germany in 1979 and is based primarily on the passive safety concept [11, 12] without the need for active systems by limiting thermal power and allowing sufficient heat losses from the reactor vessel. Its safety attribute of passive heat transfer leads to plant simplification and associated economic advantages and has the potential for being located at industrial sites.

(2) Characteristics of MHTGR

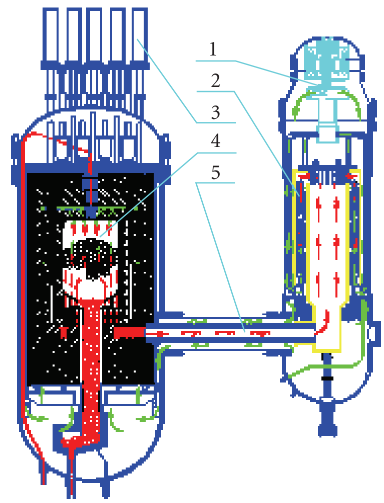
Besides all the safety characteristics of HTGRs, MHTGR adds the unique characteristic of cooling the reactor entirely by passive heat transfer mechanisms following postulated accidents without exceeding the failure temperature of the coated particles. The safety features of MHTGR were based on the design condition that, even in the event of failure of all active cooling systems and complete loss of coolant, the fuel element temperatures would remain within limits such that there is virtually no release of radioactive fission products from the fuel elements [13]. Such a condition guarantees that the MHTGR power plant would not cause any hazard to the environment either during normal operation or in the case of an accident.

With its inherent safety and capability to achieve high core outlet temperature, MHTGR has been taken as the technical basis of the Gen-IV VHTR and will become an important option for nuclear energy in the world [3]. International interest in MHTGR technology has been increasing in recent years due to a growing recognition of the potential of MHTGR designs to provide high efficiency, cost-effective electricity generation appropriate for the conditions in developing countries, and in the longer term to provide a source of high-temperature process heat. A series of national/international projects based on such technology is being carried out in dozens of countries including China, Netherlands, Russia, South Africa, UK, US, and Japan.

2.2. The MHTGR testing plant: HTR-10

The testing plant HTR-10 developed by INET of Tsinghua University was based on the pebble bed MHTGR concept. The reactor core contains about 27000 spherical fuel elements of 6 cm diameter, which form a pebble bed of 180 cm in diameter and 197 cm in average height. The mean power density is 2 MW/m^3. The reactor achieved its first criticality in December 2000. The helium temperature at the outlet of the core can reach up to 850°C. The testing plant adopted a sub-C steam turbine cycle for energy conversion. The primary helium circulation and the second steam turbine circulation were coupled by the steam generator (SG) that serves as the heat exchanger. The reactor core was designed to be installed in the reactor pressure vessel while the steam generator, the helium blower with its driving motor were installed in another separate pressure vessel, called SG pressure vessel. These two pressure vessels were arranged side by side and were connected by the horizontal coaxial hot gas duct. The hot helium from the reactor core passes through the gas duct and is fed into the SG and flows around the heating tube bundles downward. During this process, heat is transferred from the hot helium on one side of the SG to the water/steam on the other side, while the hot helium is cooled. Steam generated in the SG enters the inlet of a steam turbine and drives it to do work. The testing plant reached its full power in January 2003. During the normal operation of the testing plant, the loop pressure of the primary coolant circulation is 3.0 MPa with a mass flow-rate of 4.32 kg/s, while the inlet temperature of the reactor core is 250°C and the outlet temperature is 700°C. The SG provides the steam turbine with water steam temperature of 435°C and inlet pressure of 3.45 MPa at a mass flow-rate of 3.49 kg/s. Figure 1 describes the schematic diagram of the side-by-side arrangement of pressure vessels and the flow path of the primary loop coolant.

A series of arranged tests and experiments has been performed on HTR-10 to verify its inherent safety features and to obtain operational characteristics. It also survived a power supply shutdown accident.



1: Helium circulator
2: Steam generator
3: Control rod
4: Reactor core
5: Hot gas duct

Figure 1: The side-by-side arrangement of pressure vessels for HTR-10. (1) Helium circulator, (2) steam generator, (3) control rod, (4) reactor core, and (5) hot gas duct.

2.3. The demonstration MHTGR sub-C plant

(1) Design of MHTGR-250 reactor

Based on the successful operation of HTR-10, a demonstration MHTGR plant coupling two reactor modules with a sub-C steam turbine set was designed. The reactor is pebble bed, called MHTGR-250. It is expected to have a thermal power of 250 MW under operating pressure of 7.0 MPa with inlet/outlet temperatures of 250/750°C and a helium flux of 96.2 kg/sec (346.3 t/h). Like HTR-10, MHTGR-250 also adopts a side-by-side arrangement. The pressure drop of the primary loop was estimated to be 200 kPa. To overcome the pressure drop and drive the helium circulation of the primary loop, the compression power can be estimated by the following equation [10]:

$$W_C = \dot{m}\frac{RT\Delta P}{PM}, \qquad (1)$$

in which W_C is the compression work, $\dot{m}$ is the mass flow rate of the working medium, R is the gas constant, T is the temperature of the medium, ΔP is the pressure drop of the primary loop, P is the pressure of the working medium, and M is the molecular weight of the working medium.

For the MHTGR-250, the compression work can be calculated as $W_C = 2987$ kW. Assuming that the blower efficiency is 80% and the driving motor efficiency is 95%, the efficiency of blower with its driving motor can be expressed as $\eta_B = 80\% * 95\% = 76\%$. The required power to drive the helium blower can be calculated as

$$W_B = \frac{W_C}{\eta_B} = \frac{2987}{76\%} = 3931\,\text{kW}. \qquad (2)$$

Thus, a motor with rated power of 4000 kW was selected for an MHTGR-250 module of 250 MW.

(2) Selection of the sub-C steam turbine generation set

A mature industrial sub-C steam turbine of single reheat with a back pressure of 4.9 kPa was selected for the plant. Once-through SG was employed to couple the first closed helium loop with the second steam turbine cycle. The main steam parameters at the inlet of steam turbine are 13.5 MPa/538°C with a mass flow rate of 150 kg/sec. A mature generator was selected to yield a gross power output of 200 MWe. This plant will be put into construction as early as 2008.

The thermodynamic process of the sub-C steam turbine is a typical superheated Rankine cycle. The gross efficiency is employed to describe how much of the energy that is fed into the cycle is converted into power output:

$$\eta_{\text{st-gr}} = \frac{\text{gross power output}}{\text{heat input to the steam turbine cycle}} = \frac{W_e}{Q_{\text{st}}}. \quad (3)$$

The net efficiency also used is defined as follows:

$$\begin{aligned}\eta_{\text{st-net}} &= \frac{\text{net power output}}{\text{heat input to the steam turbine cycle}} \\ &= \frac{W_e - W_{\text{st-au}}}{Q_{\text{st}}} = \eta_{\text{st-gr}}(1 - \varphi_{\text{st}}),\end{aligned} \quad (4)$$

in which $W_{\text{st-au}}$ is the auxiliary power consumed by the steam turbine cycle and can be expressed as a ratio of the gross power output $\varphi_{\text{st}} = W_{\text{st-au}}/W_e$. The feedwater pump is likely to be the largest single consumer of auxiliary power, typically 3-4% of the gross power output.

For an MHTGR plant, the gross efficiency and net efficiency can be defined as

$$\begin{aligned}\eta_{r\text{-gr}} &= \frac{\text{gross power output}}{\text{reactor thermal power}} = \frac{W_e}{P_r}, \\ \eta_{r\text{-net}} &= \frac{\text{net power output}}{\text{reactor thermal power}} \\ &= \frac{W_e - W_{\text{st-au}} - W_{r\text{-au}}}{P_r} = \eta_{r\text{-gr}}(1 - \varphi_{\text{st}} - \varphi_r),\end{aligned} \quad (5)$$

where $W_{r\text{-au}}$ is the auxiliary power consumed by the reactor system and can be expressed as a ratio of the gross power output $\varphi_r = W_{r\text{-au}}/W_e$. The helium blower is likely to be the largest single consumer of the reactor auxiliaries, typically 3-4% of the gross power output.

The gross efficiency of MHTGR-250 sub-C plant is about $\eta_{r\text{-gr}} = 40\%$, while the net efficiency is about $\eta_{r\text{-net}} = 36.8\%$ with assumption of $\varphi_{\text{st}} = 4\%$ and $\varphi_r = 4\%$. This efficiency is slightly lower than that of the current sub-C FPP technology.

3. SC STEAM TURBINE TECHNOLOGIES

3.1. *Motivations for SC technologies*

The cycle efficiency can be improved by either increasing inlet steam parameters or decreasing the exit steam parameters or by both. The condenser pressure is determined by the available cooling water and depends on the climate and the atmospheric conditions. Thus, the available effective measure for achieving high efficiency is selecting higher steam parameters. Efficiency increases of steam turbines are being achieved by increasing the pressure and temperature at the turbine inlets well beyond the critical point of water (22.12 MPa, 374.15°C), above which the steam is at SC conditions. Modern power plants are much more complex. Two improvements have been adopted for modifying the cycle efficiency: reheat of steam and regeneration of feedwater preheating. In the regeneration process, the extracted steam from the steam turbine is used to heat up the feedwater, before it enters the boiler.

(1) Economical motivation

Most of the currently built FPPs and NPPs hold a service life of up to 40 years. The service life of next generation NPP will be up to 60 years. These plants must continue cost-effective electric power generation through their lifetime. For a power plant based on Rankine cycle, one of the most effective measures for achieving high efficiency and hence the cost-effectiveness is applying higher steam parameters, especially SC technology. The transition from sub-C to SC steam conditions significantly increases process efficiency, with a considerable decrease in fuel costs. For instance, efficiency increases by roughly 3% on making the transition from 16.7 MPa to 25 MPa, without significant increases in investment costs. Investigations show that the effect of low fuel consumption on electric power generation costs is greater than the slightly higher investment costs for the power plant.

(2) Environmental motivation

Stringent emission standard stemming from global concern about greenhouse gases is another pressure. SC FPPs with higher efficiencies have much lower gas emissions than sub-C plants for a given power output. Investigations reveal that one percent increase in efficiency reduces specific emissions such as CO2, NOx, Sox, and particulates by two percent [14]. There still exists eight percentage points (from 35% to 43%) potential for developing countries like China and India to increase the efficiencies of FPPs by applying SC power plants to reduce emissions by 15%.

3.2. *State-of-the-arts of the SC steam cycle*

An SC steam turbine set with inlet steam condition of 25 MPa/565°C for high pressure (HP) turbine and reheat temperature of 565°C for intermediate pressure (IP) turbine can achieve a net efficiency of 42% [15]. The current best available SC plant technology uses steam conditions of 30 MPa/600°C/620°C to achieve overall net plant efficiency of 46–48%, dependent upon site specific issues such as location using steels with 12–25% chromium content for the heating surfaces of boilers [15]. Nickel-based super alloys would permit 35 MPa/700°C/720°C, yielding efficiencies up to 48% [14]. Options to increase the efficiency above 50% in ASC power plants rely on elevated steam conditions as well as on improved process and component quality.

Other improvements in the steam cycle and components, such as the double reheat as well as heat extraction from flue gases, can yield a further 3 percentage points increase in efficiency. However, these technologies are not in widespread use due to their cost.

3.3. Advantages of SC technology

The principal advantages of SC steam cycles can be summarized as [16] follows:

(1) reduced fuel costs due to improved thermal efficiency;

(2) CO2 emissions reduced by about 15%, per unit of electricity generated, when compared with typical existing sub-C plant;

(3) well-proven technology with excellent availability, comparable with that of sub-C plant;

(4) very good part-load efficiencies, typically half the drop in efficiency of sub-C plant;

(5) plant costs comparable with sub-C technology and less than other clean coal technologies;

(6) very low emissions of nitrogen oxides (NOx), sulphur oxides (SOx), and particulates achievable using modern flue gas clean-up equipment.

3.4. Applications

SC plants have been continuously put into service during the past decades due to their improved characteristics, as mentioned above. Today, supercritical steam turbine cycle is the leading “clean coal” technology in widespread application. More than 500 SC power plants are operating in the world. Supercritical steam cycles are not just applicable to coal-fired plant. Oil- and gas-fired plants are also well proven and also to heat recovery steam generators (HRSGs) for combined-cycle gas turbine (CCGT) plants.

Reviewing the possibilities for the design and manufacture of components for supercritical—fired plants in developing countries, the differences between sub-C and SC power plants are limited to a relatively small number of components; primarily the feedwater pumps and the high-pressure feedwater train equipment. All the remaining components that are common to sub-C and SC coal-fired power plants can be manufactured in developing countries.

4. CONCEPTUAL DESIGN OF MHTGR SC PLANTS BASED ON MHTGR-250

4.1. Prospective deployments of MHTGR SC plants

It is recognized that an SC Rankine cycle plant with up to 250 MW will be unlikely to achieve the same high efficiencies as a larger output machine, mainly due to increased blade-path losses in the HP turbines [16]. The pebble bed MHTGR reactor module should be maintained at a moderate power level, say 200–400 MW, to retain inherent safety. Therefore, the suitable deployment of MHTGR SC plant should be multiple reactor modules coupling with one steam turbine set.

There are two SC steam cycle modes for MHTGR plants as follows:

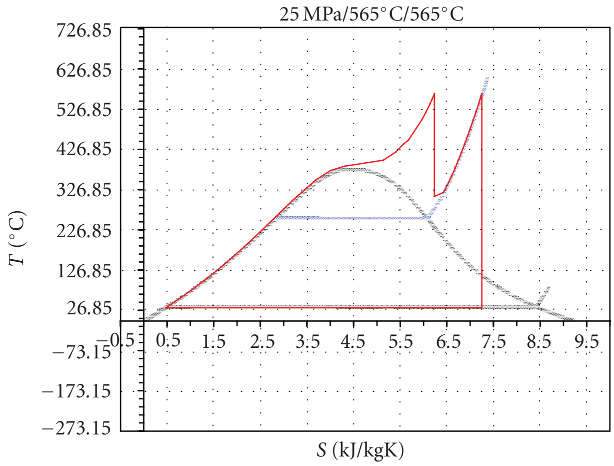


Figure 2: Ideal T-S diagram of once-reheat SC Rankine cycle with 25 MPa/565°C/565°C.

(1) the standard once-reheat SC steam cycle of which the steam from HP will be sent to the steam generator vessel for reheat by the primary loop helium;

(2) the SC steam cycle with reheat by life steam separated from the outlet of the steam generator.

4.2. MHTGR-250 SC plant with a standard once-reheat SC cycle

4.2.1. Selection of the SC steam turbine set

It is a reasonable selection for MHTGR-250 SC plant to adopt standard commercial once-reheat steam turbine set. Two classes of standard commercial steam turbine sets for FPPs are available in China market: 25 MPa/565°C/565°C and 26.25 MPa/600°C/600°C. Such power plants have been built often enough in China today, so that this turbine technology can be assumed mature and reliable. To assure the reliability and economic competitiveness, the matured commercial 600 MW SC steam turbine set with 25 MPa/565°C/565°C is selected for the MHTGR-250 SC plant. Figure 2 illustrates its ideal temperature-entropy diagram.

4.2.2. Matching patterns of reactor modules with steam turbine sets

To match a 600 MW steam turbine set with 25.0 MPa/565°C/565°C, 5 modules of MHTGR-250 with 250 MW will be needed. Two matching patterns are investigated.

(1) Matching pattern 1

For this matching pattern, four modules of MHTGR-250 250 MW are designed to supply the life steam of 25.4 MPa/571°C to HP turbine, while one MHTGR-250 module with 234 MW is designed to supply the reheat steam of 4.19 MPa/569°C. The matching pattern and corresponding steam parameters are illustrated in Figure 3.

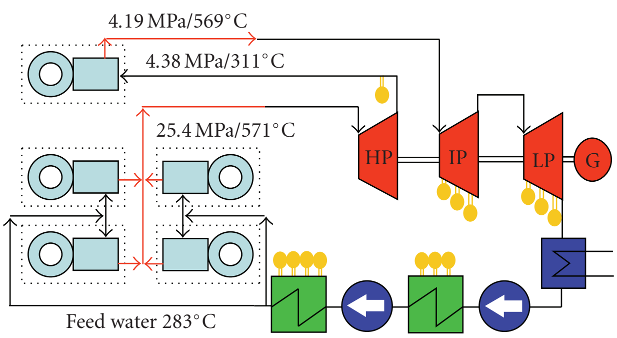


Figure 3: Matching pattern 1 of MHTGR-250 SC plant.

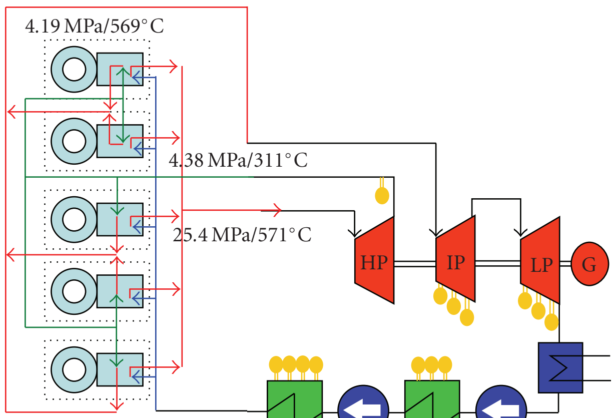


Figure 4: Matching pattern 2 of MHTGR-250 SC plant.

(2) Matching pattern 2

Unlike the matching pattern 1, each MHTGR-250 module is designed to supply both the life steam of 25.4 MPa/571°C and the reheat steam of 4.19 MPa/569°C. The matching pattern and corresponding steam parameters are illustrated in Figure 4.

4.2.3. Design of SG, reheat exchangers, and helium blower

(1) SG for the life steam supplier

For the selected turbine set, the feedwater temperature is 283°C, while the SC steam parameters at SG outlet are 25.4 MPa/571°C.

For the helium side of SG, the inlet temperature is kept at 750°C to maintain 179°C temperature difference between the helium and the SC steam for effective heat transfer. The outlet helium temperature should be increased from 250°C for the standard MHTGR-250 design to 330°C to maintain effective heat transfer between the helium and the feedwater.

Although high steam pressure and temperature involves modifications of the once-through SG and relevant pipes, no additional difficulties in design and manufacture are expected.

(2) Reheat exchanger for reheat steam supply

For the selected turbine set, the steam parameters at the inlet of the reheat exchanger are 4.38 MPa/311°C and 4.19 MPa/569°C at the outlet. For the helium side of reheat exchanger, the helium temperature at both inlet and outlet should be 350°C/750°C.

(3) Helium blower

For the MHTGR-250 module with rated power of 250 MW and inlet/outlet temperature of 330°C/750°C, the helium flow rate of the primary loop should be 114.51 kg/s to transfer 250 MW thermal power. Flow paths of the primary loop should be designed to reduce the circulation pressure drop, say 150 kPa. The compression power to maintain the circulation can be calculated by (1) : $W_C = 3075$ kW.

Also assume a complex efficiency of the helium blower $\eta_B = 80\% * 95\% = 76\%$, the required power to drive the helium blower can be calculated as $W_B = W_C/\eta_B = 3075/76\% = 4046$ kW.

For the MHTGR-250 module with thermal power of 234 MW and inlet/outlet temperature of 350°C/750°C, the helium flow rate of the primary loop should be 112.54 kg/s to transfer 234 MW thermal power. Also assume a pressure drop of 150 kPa, the compression power to maintain the circulation can be calculated as $W_C = 3122$ kW. The required power to drive the helium blower should be $W_B = W_C/\eta_B = 3122/76\% = 4108$ kW.

4.2.4. Efficiencies of the MHTGR-250 SC plant

By selecting a standard commercial SC steam turbine set, the same characteristics of the steam turbine cycle can be expected. For estimating the efficiencies of the MHTGR-250 SC plant, we should first calculate the efficiencies of the FPP with the same steam turbine set. Secondly, the efficiencies of the steam turbine cycle will be calculated.

(1) Efficiencies of the FPP with 25 MPa/565°C/565°C

A 600 MWe FPP with 25 MPa/565°C/565°C can achieve a net plant efficiency $\eta_{f\text{-net}} = 42\%$, the auxiliary power consumption is 7.5% of the gross electricity output [17]. Thus, the gross electricity output is $W_e = W_{\text{net}}/(1 - 7.5\%) = 648.65$ MWe and the gross plant efficiency is

$$\eta_{f\text{-gross}} = \frac{\eta_{f\text{-net}}}{1 - 7.5\%} = 45.4\%. \qquad (6)$$

(2) Efficiencies of the steam turbine cycle

The average fuel efficiency of the boiler fired by bituminous coal in China is $\eta_f = 93\%$. Assume the power consumption rate of the pumps for the steam turbine cycle is 4%, the gross efficiency and net efficiency of the steam turbine cycle can be calculated as follows:

$$\eta_{\text{st-gross}} = \frac{\eta_{f\text{-gross}}}{\eta_f} = \frac{45.4\%}{93\%} = 48.8\%,$$
$$\eta_{\text{st-net}} = \eta_{\text{st-gross}}(1 - 0.04) = 46.85\%. \tag{7}$$

(3) Efficiencies of the MHTGR-250 SC plant

For a MHTGR-250 SC plant, the compression work is converted to thermal energy of the helium. Thus, the total heat transferred to water/steam of the secondary loop should be the reactor power plus the compression work. Take the matching pattern 2 as an example, the total heat accepted by water/steam is $Q_{\text{st}} = 5 \times (250 + 4.046) = 1270.2\,\text{MW}$. The gross electricity output should be

$$W_e = Q_{\text{st}} \times \eta_{\text{st-gross}} = 1270.2 \times 48.8\% = 619.86\,\text{MW}. \tag{8}$$

The gross efficiency should be

$$\eta_{r\text{-gross}} = \frac{W_e}{Q_r} = \frac{619.86}{1250} = 49.6\%. \tag{9a}$$

Assume that the reactor auxiliary systems including the helium blower consume another 4% of the gross electricity output, the net efficiency of the MHTGR SC plant is

$$\eta_{r\text{-net}} = \eta_{r\text{-gross}}(1 - 4\% - 4\%) = 45.62\%. \tag{9b}$$

Compared with the net efficiency of 35% achieved by AP1000, the net efficiency of MHTGR-250 SC plant is 10.62 percentages higher (relatively higher by 30.2%). For a plant with service life of 40 to 60 years, such an improvement in efficiency is of extreme technical advance.

4.3. MHTGR-250 SC plant with a life steam reheat SC cycle

The deployment mode of MHTGR-250 SC plant with a standard once-reheat steam turbine set has some shortcomings: the matching pattern 1 will reduce the high availability factor of SC steam turbine set; the matching pattern 2 requires that each reactor module needs to be equipped with both SG and reheat exchanger. The complicated structures of the SG pressure vessel and corresponding pipes result in additional pressure drops.

With respect to the above mentioned shortcomings of the MHTGR-250 SC plant with standard once-reheat steam cycle, another deployment should be considered: using the separation of life steam to reheat the steam from the HP. For such a deployment, the HP turbine should be redesigned to fit an inlet temperature higher than the reheat steam.

4.3.1. Deployment mode of reactor modules with steam turbine sets

The deployment mode is described in Figure 5: five MHTGR-250 modules couple one steam turbine set. The main part of the life steam from the SG exit enters HP turbine for expansion to do work. The steam from HP turbine exit is reheated by the other part of the life steam and enters IP and LP turbines for further expansion to the set back pressure and drought.

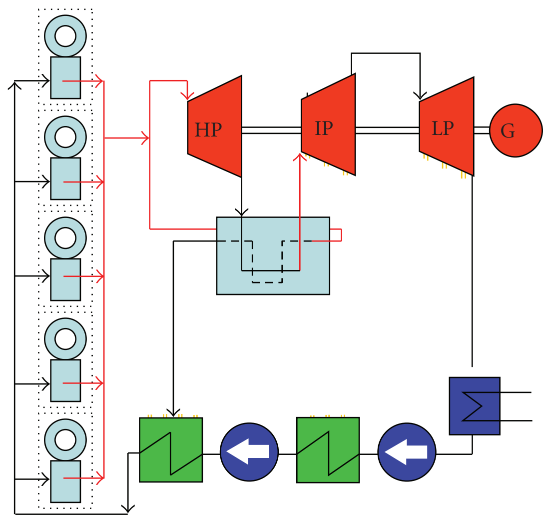


Figure 5: Deployment mode of MHTGR-250 SC plant with life steam reheat cycle.

4.3.2. Matching pattern 1 based on matured SC turbine techniques

The highest techniques of matured steam turbine in China are 26.25 MPa/600°C/600°C. Thus, the inlet steam parameters for HP turbine can be selected to be 26.25 MPa/600°C. The corresponding steam parameters at SG exit should be 27.5 MPa/605°C. Considering the temperature difference for the effective heat transfer during the reheat process, the reheated steam temperature can be set to be 569°C so that the IP and LP techniques of another matured turbine set of 25 MPa/565°C/565°C can be used. The steam parameters at inlet and outlet of the reheat exchanger are 4.38 MPa/311°C and 4.19 MPa/569°C, respectively. The ideal temperature-entropy diagram of the life steam reheat turbine cycle with 26.25 MPa/600°C/565°C is illustrated in Figure 6.

4.3.3. Matching pattern 2 based on ASC turbine techniques

During the last decade, Denmark has accumulated a lot of experience in ASC steam turbine sets, most of which adopt twice-reheat steam cycle. The steam parameters for those turbine sets fall in the range of 28–30 MPa/580–600°C/580–600°C/580–600°C with a plant capacity of about 400 MW. Some companies in Japan have been developing Ultra SC turbine techniques with 34.5 MPa/620°C/650°C, 31 MPa/593°C/593°C/593°C, and 34.4 MPa/649°C/593°C/593°C.

In seeking to maximize the efficiency of coal-fired power plants and at the same time minimize the environmental effects, European industry, including both manufacturers

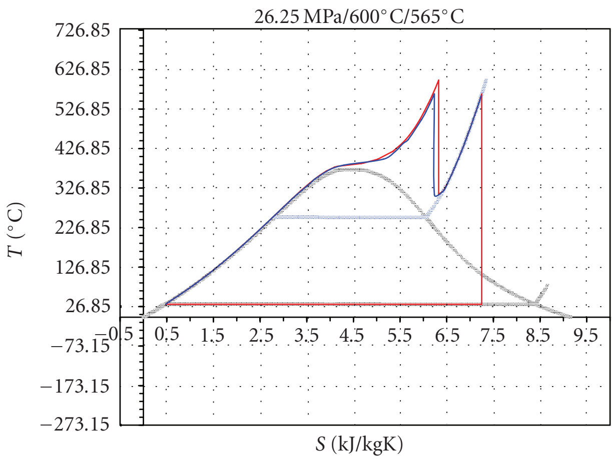


Figure 6: Ideal T-S diagram of life-steam reheat SC turbine cycle with 26.25 MPa/600°C/565°C.

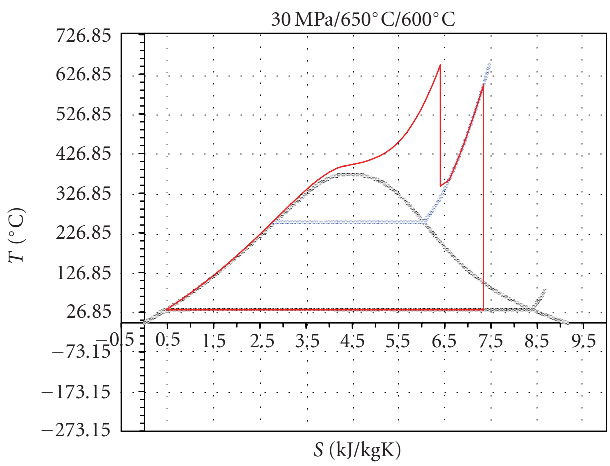


Figure 7: Ideal T-S diagram of life-steam reheat ASC turbine cycle with 30 MPa/650°C/600°C.

and power generators, launched the AD700 program. Future PF-fired ASC power plant currently under development in the AD700 project will achieve 50–55% net efficiency. To achieve these efficiencies a step-change in steam conditions to 35 MPa/700°C/720°C is necessary. AD700 ASC PF boiler and turbine technology are expected to become available before 2010 [15].

Based on the current status of turbine techniques, the inlet steam parameters for HP turbine of the MHTGR ASC plant can be selected to be 30 MPa/650°C. Considering the temperature difference for effective heat transfer during the reheat process, the reheated steam temperature can be set to be 605°C so that the IP and LP techniques of the matured turbine set of 26.25 MPa/600°C/600°C can be used.

The steam parameters at HP exit are 4.73 MPa/345°C, while the reheat steam parameters at the IP inlet are 4.25 MPa/600°C, respectively. The ideal temperature-entropy diagram of the life steam reheat ASC turbine cycle with 30 MPa/650°C/600°C is illustrated in Figure 7.

4.4. Comparisons between deployment modes of MHTGR SC/ASC plants

4.4.1. Standard once-reheat mode

(1) Advantages

The deployment mode of standard once-reheat steam cycle for the MHTGRSC plant can adopt the matured commercial SC steam turbine sets. Both the life steam and the reheat steam can reach a high-temperature to achieve a relatively higher efficiency. This leads to the following principal advantages: (i) higher efficiency than that of APWR, comparable with that of SC FPPs, (ii) plant costs comparable with MHTGR sub-C plant.

(2) Disadvantages

(i) The matching pattern 1 as described in Figure 3 will lose the advantage of SC steam turbine technology: very good part-load efficiencies and excellent availability.

(ii) The matching pattern 2 as described in Figure 4 requires that each reactor module needs to be equipped both SG and reheat exchanger. The complicated structures of the SG pressure vessel and corresponding pipes result in additional pressure drops.

4.4.2. Life steam once-reheat mode

(1) Advantages

(i) Higher efficiency than that of APWR comparable with that of SC FPPs;

(ii) plant costs comparable with MHTGR sub-C plant;

(iii) simplification of the once-through SG comparable with that of the MHTGR sub-C plant;

(iv) excellent availability, better than that of existing SC FPPs due to the MHTGR refuel mode;

(v) very good part-load efficiencies, typically half the drop in efficiency of sub-C plant.

(2) Disadvantages

The deployment mode of life-steam reheat cycle for the MHTGR SC plant requires that reheat steam temperature is lower than the life steam for effective heat transfer. This will result in a slightly lower efficiency than that of the standard once-reheat steam cycle.

No matured commercial SC/ASC steam turbine is available. The HP should be redesigned to fit the higher pressure/temperature of life steam.

5. CONCLUSION

Energy conversion efficiency of Rankine cycle power plants can be improved largely by increasing the main steam parameters. For instance, efficiency increases by roughly 3% on making the transition from sub-C state of 16.7 MPa to SC state of 25 MPa. The possible combination of MHTGR technology with SC steam turbine technology was investigated. The prospective deployments of MHTGR-250 SC plants were discussed based on both the features of SC steam turbine cycle and the features of MHTGR. The standard once-reheat SC steam turbine cycle and the life steam reheat cycle have been studied and corresponding parameters were computed. Efficiencies of thermodynamic processes of MHTGR SC plants were analyzed, while comparisons were also made between an MHTGR-250 SC plant and a designed advanced passive PWR (AP1000). It was shown that the net plant efficiency of an MHTGR-250 SC plant is equivalent to (or even higher than) that of an SC FPP (45% or above), 30% higher than that of AP1000 (35% net efficiency). At present and in the foreseeable future, the MHTGR-250 SC/ASC plants appear the prospective high efficiency NPP types.

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