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Combined cycle schemes coupled with a Very High Temperature gas-cooled reactor

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ABSTRACT

With gradual increase in reactor outlet temperature, the efficient power conversion technology has become one of developing trends of (very) high temperature gas-cooled reactors (HTGRs/VHTRs). In this paper, physical and mathematical models of two combined cycle schemes coupled with the VHTR, Reheated Combined Cycle (RCC) and Regenerative-Reheated Combined Cycle (RRCC), are established. Their topping cycle is a no precooling and no intercooling Brayton cycle, and their bottoming cycle is a supercritical Rankine cycle. The effects and mechanism of key parameters were analyzed. Based on parameter analysis, two schemes were compared within the temperature range of the VHTRs (ROT 950–1200 °C). The analysis shows that, for the combined cycle of the VHTR, by adding a recuperator, can further utilize the helium turbine exhaust heat, then to improve the cycle efficiency. When the ROT is 1050 °C, the cycle efficiency of the RRCC (recuperator's effectiveness 0.4) is 56.4%, which is 2.18% higher than that of the RCC. But because of the regenerative process, the reactor inlet temperature (RIT) of the RRCC is higher than 490 °C, additional reactor pressure vessel (RPV) cooling system is necessary, and it increases the system complexity and reduce the cycle's efficiency. The RIT of the RCC can be controlled below 490 °C, no RPV cooling system is required. Amongst the main parameters, the recuperator's effectiveness and compression ratio are the most important factor affecting the cycle efficiency of the VHTR. The cycle efficiency can be increased by 0.61% when the recuperator's effectiveness is increased by 0.1. The main factors that limit the increase of the recuperator's effectiveness are the RIT and the system flow resistance. When the average compression ratio increases by 0.1, the combined cycle efficiency increases by 0.33% (RCC) and 0.373% (RRCC). The main factors that limit the increase of compression ratio are the manufacturing capacity of magnetic bearings, turbines and compressors. These results provide insights on the combined cycle of the VHTRs, and reveal the effects of key parameters on performance of these cycles. It could be helpful to understand and develop a combined cycle coupled with a VHTR in the future.

1. Introduction

The high temperature gas-cooled reactor (HTGR) is a nuclear reactor with internationally-recognized inherent safety. It has high power generation efficiency, and can obtain high temperature for wide application. It uses the TRISO-coated particle fuel elements, and a full ceramic core structure, with helium as coolant and graphite as moderator. The HTGR is one of Generation-IV reactors expected to be fully matured for commercialization in the period between 2020 and 2030 or beyond (Abram and Ion, 2008; Bardia, 1980. With development of materials, the reactor outlet temperature (ROT) of the helium coolant is gradually elevated. When the ROT is higher than 950–1000 °C (Chapin et al., 2004), the reactor is defined as Very High Temperature gas-cooled Reactor (VHTR). In the evolution process of HTGR to VHTR, as the ROT increases, different power conversion units (PCU) would be required to transfer the core heat and efficiently convert it into electrical energy. At present, PCU of HTGR includes the Rankine cycle, the closed Brayton cycle and the combined cycle.

In Rankine cycle, the helium cools the reactor and transfers heat to the feed water in steam generator. After the feed water is evaporated in steam generator, it drives the steam turbine to work, and heat is finally converted into the output power. The Rankine cycle scheme is mainly used in the early and current HTGR projects and it has made a large progress in some countries. The major steam cycle projects of different countries are listed in Table 1.

The closed Brayton cycle can be applied in many different areas. And Olumayegun O (Olumayegun et al., 2016) made a detailed review of closed Brayton cycle. Various researches on the power cycles for

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Abbreviations and nomenclature

SCC	Simple Combined Cycle
s	Specific Entropy
RCC	Reheated Combined Cycle
t	Temperature
RRCC	Regenerative-Reheated Combined Cycle
HRSG	Heat Recovery Steam Generator
q	Heat Absorption
HTGR	High Temperature gas-cooled Reactor
w	Output Work
RIT	Reactor Inlet Temperature
x	Exhaust Steam Humidity
ROT	Reactor Outlet Temperature
α	Recuperator's Effectiveness
RPV	Reactor Pressure Vessel
γ	Compression Ratio
VHTR	Very High Temperature Gas-cooled Reactor
τ	Temperature Ratio
PCU	Power Conversion Union
η	Cycle Efficiency
M	Mass Flow
β	Flow percentage for cooling the turbine
Cp	Specific Heat at Constant Pressure
ε	Resistance Coefficient
i	Specific Enthalpy
φ	Gas Constant of Helium
t	Temperature
ΔTb	Temperature Difference at Hot End in HRSG(TDHE)
p	Pressure
ΔTc	Temperature Difference at Cold End in HRSG(TDCE)
q	Heat Quantity

Subcript

b	Bottoming Cycle
gt	Topping Cycle Output Work
B	Brayton Cycle
st	Bottoming Cycle Output Work
CC	Combined Cycle
T	Topping Cycle
t	Helium Turbine
C	Helium Compressor

Table 1

Typical HTGR programs and their main parameters (Simnad, 1991; Wang et al., 2014).

Cycle schemes	Programme/Plant	Country	Rating MWt	ROT °C	Effic.%	Design or Operation Years
Steam Cycle	Dragon	U.K	20	750	–	1965–1975
	UHTREX	USA	3	1350	–	1966–1970
	PB 1	USA	115	725	35	1967–1974
	AVR	Germany	46	750–950	30	1967–1988
	FSV	USA	842	775	39	1976–1989
	THTR-300	Germany	750	750	39	1985–1991
	HTTR	Japan	30	950	–	1998-
	HTR-10	China	10	700	20	1995-
	HTR-PM	China	250 × 2	750	40	2001-
	SC-HTGR	USA	625	750	43.5	2009-
	HTMR-100	Africa	100 × 4	750	35	2012-
	Xe-100	USA	100	750	35	2013-
Closed Brayton Cycle	GT-HTGR	USA	3000	850	40	1970–1982
	PBMR	S.Africa	400	900	42.2	1998–2009
	GT-MHR	USA & Russia	600	850	47.7	1994-
	GTHTR300	Japan	600	850	46.8	1994-
	HTR-10GT	China	10	750	20.2	2004-
Combined Cycle	ANTARES	France	600	850	47	2004
	NGTCC	USA	350	950	51.5	Designed Cycle

Generation-IV indicated closed Brayton cycle as promising alternatives to the current Rankine cycles (Dostal et al., 2004) (Zhao and Peterson, 2008) (Cha et al., 2009) (Kelly and Generation, 2014). In the closed Brayton cycle of HTGR, helium compressed by a helium compressor cools the reactor core, and then enters directly into the helium turbine where it expands to work. At present helium turbine cycle scheme is adopted and developed in GT-HTGR (McDonald, 2010; McDonald et al., 1976) in USA, PBMR (Matzner, 2004) in South Africa, GT-MHR (Baxi et al., 2008) in the United States and Russia, GTHTR300 (Yan et al., 2003) in Japan and HTR-10GT (Huang et al., 2004) in China. In these schemes, a recuperator is added to improve cycle efficiency. High recuperation effectiveness ensures high cycle efficiency, but causes higher reactor inlet temperature (RIT) at the same time. However, RIT is limited by the material of the RPV. At present, material of the pressure vessel mainly includes two options: the SA533 steel and 9Cr1MoV steel (Wang, 2002). The main advantages of the SA533 steel are relatively mature, and have been widely used in the pressurized water reactor. The allowed temperature limit for SA533 steel is 370 °C. The 9Cr1MoV steel has upper limited temperature of 490 °C. But the 9Cr1MoV steel has never been used in any type of reactors (Wang, 2002). When RIT is higher than 490 °C, it is necessary to take the inner cooling measure to keep the safety of the RPV. A part of cold helium can be diverted from the high-pressure compressor outlet to cool the pressure vessel so that the temperature of pressure vessel is maintained within the allowable range.

The combined cycle is a scheme coupled a helium closed Brayton cycle with the steam Rankine cycle. The closed Brayton cycle is the topping cycle and the Rankine cycle is the bottoming cycle, and the helium turbo-compressors and steam turbines are connected to the generator to generate electricity at the same time. This combined cycle scheme can not only effectively take advantage of the high temperature heat source of HRSG, but also avoid the problem of pressure vessel structure material. Now the combined cycle scheme of HTGR remains in the conceptual design stage. AREVA (Gauthier et al., 2006) designed a combined cycle scheme for an VHTR with a reactor outlet temperature of 1000 °C. The scheme is a three-loop combined cycle. In the primary circuit helium transfers heat released by the reactor to the Brayton cycle of the secondary circuit through the intermediate heat exchanger. The