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A study on different thermodynamic cycle schemes coupled with a 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). In this paper, different cycle power generation schemes for HTGRs were systematically studied. Physical and mathematical models were established for these three cycle schemes: closed Brayton cycle, simple combined cycle, and reheated combined cycle. The effects and mechanism of key parameters such as reactor core outlet temperature, reactor core inlet temperature and compression ratio on the features of these cycles were analyzed. Then, optimization results were given with engineering restrictive conditions, including pinch point temperature differences. Results revealed that within the temperature range of HTGRs (700–900 °C), the reheated combined cycle had the highest efficiency, while the simple combined cycle had the lowest efficiency (900 °C). The efficiencies of the closed Brayton cycle, simple combined cycle and reheated combined cycle are 49.5%, 46.6% and 50.1%, respectively. These results provide insights on the different schemes of these cycles, 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 high temperature reactor in the future.

1. Introduction

The high temperature gas-cooled reactor (HTGR) is a nuclear reactor type with internationally-recognized inherent safety, high power generation efficiency and wide application. This uses the coated particle fuel elements TRISO, and a full ceramic core structure, with helium as coolant and graphite as moderator. The reactor outlet temperature (ROT) of the helium coolant is elevated to above 900 °C or higher, based on the HTGR. In this case, the reactor is a very high temperature gas-cooled reactor (VHTR). In the development process of HTGR to VHTR, as the helium outlet temperature becomes higher, different power conversion units (PCU) would be required to transfer the core heat and efficiently convert it into electrical energy. At present, HTGR PCU includes the steam cycle, the closed Brayton cycle (CBC) and the combined cycle.

The steam cycle is a two-loop cycle. In primary circuit, the helium cooling reactor transfers heat into the intermediate heat exchanger (steam generator) and heats the secondary feedwater. After the feedwater is evaporated, it drives the steam turbine to work, and heat is finally converted into the output power. The steam cycle scheme is mainly used in the early HTGR reactor projects. The major steam cycle projects of different countries are listed in Table 1.

In the CBC, helium compressed by a helium compressor cools the reactor core, and then enters directly into the helium turbine where it expands to work. The present helium turbine direct cycle scheme is mainly used in 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 recuperation cycle is added on the basis of the Brayton cycle in order 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 reactor vessel structure. At present, structure material of the pressure vessel mainly includes two options: the SA533 steel and 9Cr1MoV steel (Wang, 2002). Of which, the SA533 steel has the advantages that the technology is relatively mature, and it has been widely used in the pressurized water reactor. The allowed temperature limit for SA533 steel is 370 °C. The 9Cr1MoV steel has a limited temperature of 490 °C. But the 9Cr1MoV steel has never been applied in any type of reactors (Wang, 2002). When RIT is higher than the limited temperature of the SA533 steel and 9Cr1MoV,

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Nomenclature

Abbreviations

CBC	Closed Brayton Cycle
CC	Combined Cycle
SCC	Simple Combined Cycle
RCC	Reheated Combined Cycle
HRSG	Heat Recovery Steam Generator
HTGR	High Temperature gas-cooled Reactor
RIT	Reactor Inlet Temperature
ROT	Reactor Outlet Temperature
RPV	Reactor Pressure Vessel
VHTR	Very High Temperature Gas-cooled Reactor
PCU	Power Conversion Union
A	Heat Transfer Area
i	Specific Enthalpy
p	Pressure
q	Heat Quantity
s	Specific Entropy
t	Temperature
w	Output Work
x	Exhaust Steam Humidity
γ	Compression Ratio
η	Cycle Efficiency
ΔT_{gw}	Pinch Temperature Difference
ΔT_{m} LMTD	Logarithmic Mean Temperature Difference
ΔT_{b}	Temperature Difference at Hot End of HRSG
K	Heat Transfer Coefficient
ΔT_{c}	Temperature Difference at Cold End of HRSG

Subcript

b	Bottoming cycle
B	Brayton cycle
gt	Topping cycle output work
st	Bottoming cycle output work
t	Topping cycle

Table 1
Typical HTGR Programs and Their Main Parameters (Simnad, 1991; Ming, 2009).

Schemes	Name	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-
Helium Turbine Direct Cycle	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

there is necessary for the inner cooling of reactor pressure vessel. A part of cold helium can be diverted from the high pressure compressor outlet to cool the pressure vessel so that the pressure vessel is maintained within the allowable temperature range.

The combined cycle couples a helium Brayton cycle with the steam Rankine cycle. The former is the topping cycle and the latter is the bottoming cycle, and the helium and steam turbines are connected to the generator to output power at the same time. This combined cycle scheme can not only effectively use of the high temperature heat source of HRSG, but also solve the problem, in which the pressure vessel structure material in the helium turbine direct cycle is limited when the reactor outlet temperature rises. 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 turbine inlet temperature is 950 °C. In the third circuit the steam generator transfers the exhaust heat of the helium turbine to the Rankine cycle. The design of AREVA is relatively complex, and the 1000 °C high temperature heat source is not directly used. McDonald (McDonald, 2014, 2010) designed subcritical and supercritical combined cycles, for VHTR with a reactor outlet temperature of 950 °C. McDonald only provided the design scheme, did not introduce the calculation model and the corresponding restrictions, and did not analyze and compare the parameters. In addition Wang Jie (Wang et al., 2014, 2015, 2016) designed a simplified combined-cycle scheme and a complex combined-cycle scheme, and compared the two schemes. The design of Wang Jie was based on the thermal power combined cycle design. However, heat recovery steam generators (HRSGs) in thermal power plants are too complex for HTGRs. In addition, in the combined cycle, Wang Jie did not consider some specific constraints such as that the helium compressor should satisfy current technical conditions. Furthermore, excessive compression ratios would bring manufacturing difficulties to the helium compressor and magnetic bearing.