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A novel nuclear combined power and cooling system integrating high temperature gas-cooled reactor with ammonia–water cycle

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ABSTRACT

A nuclear ammonia–water power and refrigeration cogeneration system (NAPR) has been proposed and analyzed in this paper. It consists of a closed high temperature gas-cooled reactor (HTGR) topping Brayton cycle and a modified ammonia water power/refrigeration combined bottoming cycle (APR). The HTGR is an inherently safe reactor, and thus could be stable, flexible and suitable for various energy supply situation, and its exhaust heat is fully recovered by the mixture of ammonia and water in the bottoming cycle. To reduce exergy losses and enhance outputs, the ammonia concentrations of the bottoming cycle working fluid are optimized in both power and refrigeration processes. With the HTGR of 200 MW thermal capacity and 900 °C/70 bar reactor-core-outlet helium, the system achieves 88.8 MW net electrical output and 9.27 MW refrigeration capacity, and also attains an energy efficiency of 69.9% and exergy efficiency of 72.5%, which are higher by 5.3%-points and 2.6%-points as compared with the nuclear combined cycle (NCC, like a conventional gas/steam power-only combined cycle while the topping cycle is a closed HTGR Brayton cycle) with the same nuclear energy input. Compared with conventional separate power and refrigeration generation systems, the fossil fuel saving (based on CH_4) and CO_2 emission reduction of base-case NAPR could reach ~9.66 × 10^4 t/y and ~26.6 × 10^4 t/y, respectively. The system integration accomplishes the safe and high-efficiency utilization of nuclear energy by power and refrigeration cogeneration.

1. Introduction

Nuclear energy, clean without green-house gas or dust emissions, could release energy as stably as the fossil fuel and hence could replace the latter massively. It has become an inevitable strategic option for China to develop nuclear power. In "the 12th five-year plan of energy development" published in 2012, the Chinese government declared to recover the construction of nuclear power soundly [1–4]. By the end of 2011, China has 7 nuclear power plants coming into service, with installed capacity of 12,570 MW. Meanwhile, 13 nuclear power plants with installed capacity of 33,970 MW are under construction, ranking the first place in the world [4]. In 2015, the total installed capacity for nuclear power will be over 40,000 MW [2].

For the third-generation nuclear power technology, most of the reactors are pressurized light water reactors (PWR), in which the working fluid is H_2O and the reactor core outlet temperature is not high (~324 °C/15.5 MPa), leading to a limited power generation efficiency (~33%). In order to improve the safety and the efficiency, the forth-generation nuclear power technology has been developed, in which the high temperature gas-cooled reactor (HTGR) is one of the most potential technologies. Since the middle of last century, HTGRs have been built in many countries. In South Africa, the PBMR (Pebble Bed Modular Reactor) project approaches the construction phase of the plant [5]; in China and Japan there are small test reactors HTR-10 (High Temperature Reactor-10) [6–7] and HTTR (High Temperature engineering Test Reactor) [8]; the GTMHR (Gas Turbine-Modular Helium Reactor) [9] has attracted the participation of the United States, Russia, France and Japan. The HTGR has two characters:

(1) **Inherent safety**, the HTGR is impossible to reach a state where radioactive fission products would set free above predefined levels [10–13] because of its distinctive configuration and inertia of the coolant, helium.

In HTGR, the fuel is dispersed in billions of coated particles (~0.5 mm diameter). The high-density coatings contain tough silicon carbide ceramic, which serves as a miniature pressure

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Nomenclature

COT	core outlet temperature (°C)
COP	coefficient of performance
E	exergy (kW) or (MW)
h	enthalpy (kJ/kg)
m	mass flow (kg/s)
Q	quantity of heat (MW)
s	entropy (kJ/kg K)
SF_1	split fraction of splitter SPL1
SF_2	split fraction of splitter SPL2
T	temperature (K)
t	temperature (°C)
VF	vapor fraction
W	work output (MW)
X	ammonia mass fraction of the basic solution

Greek symbols

η	energy efficiency
ε	exergy efficiency
π	pressure ratio
Δt_p	pinch point temperature difference (°C)

Subscripts and superscripts

a	ambient state
EVA	evaporator
in	input
NER	nuclear energy reactor
min	minimum
net	net value
o	output
1, 2, ...	stream numbers

vessel that can retain fission products up to temperatures of 1600 °C. After the coated particles loaded into graphite fuel elements, the elements are placed into a metal pressure vessel in which they are surrounded by a shield of graphite blocks that functions as a reflector and moderator [11].

(2) The temperature of reactor-core-outlet helium could achieve over **900 °C**. To make good use of the high-temperature helium, the HTGR-matching thermodynamic cycles are under discussion and research.

Two approaches, the HTGR regenerated cycle and the HTGR combined cycle, have been proposed to recovery the helium exhaust heat and convert it into power output.

In HTGR regenerated cycle, the working fluid is helium and the thermal efficiency could reach 47.9% [14]. However, the heat capacity of the gas–gas heat regenerator becomes as large as that of the reactor, which results in bulky equipments and complicated processes. What is more, the temperature of the reactor-core-inlet helium will get too high (550 °C [14]) after being pre-heated by internal heat recuperation process, which results in expensive heat-resistant alloy steel application at the core entrance or some kind of an extra cooling system at the cost of efficiency droop [5,9].

Due to the high efficiency of the natural gas (NG) combined cycle, the HTGR combined cycle is predicted to have good thermal performances. Meanwhile, the core inlet temperature could be controlled to a moderate level (<350 °C) without preheating, and the whole helium-heating process is only in the reactor core [6,7]. In preliminary simulation, the thermal efficiency could get 48.7%/51.4%/54.2% if the core outlet temperature reaches 950 °C/1050 °C/1150 °C [10,12–14].

To achieve better performances, Yu, Chen and co-workers adopted Kalina cycle as the bottoming cycle instead of using the conventional Rankine cycle in HTGR combined cycle [15,16]. The research did not give exact values of the work outputs or efficiencies of the HTGR-Kalina combined cycle. Investigations on the effects of the main parameters found that the raise of the temperature ratio in topping cycle is in favor of enhancing the power output and thermal efficiency of the whole combined cycle.

It is worth noting that ammonia is also a widely used refrigerant. Different ammonia–water based systems have been proposed for power/refrigeration cogeneration. Goswami et al. used the ammonia-rich vapor separated by flash tank as the turbine working fluid to generate power, and the turbine exhaust provides cooling by transferring sensible heat to the chilled water [17]. Zheng and co-workers then proposed a combined cycle which replaces the flash tank with a rectification column in the Kalina cycle, and the ammonia enriched distillation is throttled to produce refrigeration and then mixes with the main working fluid for power generation [18]. In the ammonia water power/refrigeration cogeneration system (APR) proposed by Liu and Zhang, some splitting/absorption units were introduced, thus various ammonia concentrations were obtained to meet different demands in heat exchange and other processes. The exergy efficiency reached 58% for the base case (turbine inlet 450 °C/11.1 MPa and refrigeration temperature below −15 °C) [19].

For high-efficiency utilization of the nuclear energy, a modified APR cycle has been integrated with HTGR in this paper, and hence a nuclear ammonia–water power/refrigeration cogeneration system (NAPR) has been proposed. Attention has been paid to the helium turbine exhaust heat recovery in both steam-generation and distillation processes in the modified bottoming APR cycle. The system has been simulated with ASPEN PLUS software [20], and the thermodynamic performances have been analyzed. The preliminary environmental performance discussion and parametric analysis also have been carried out.

2. System configuration description

As shown in Fig. 1, the topping cycle of the NAPR system is a closed helium Brayton cycle (stream 1–7), and the bottoming cycle is a modified APR cycle (stream 8–29).

In the closed Brayton cycle, the helium sent into the compressor (stream 1) is compressed and then fed into the nuclear energy reactor (NER, HTGR type) (stream 2). After heated to around 900 °C (stream 3), the high-temperature helium expands in the helium turbine and generates power. The residual heat of the turbine exhaust (stream 4) is recovered in boiler (B), rectifier (REC) and heat exchanger (HEX1) in sequence. Afterwards, the cooled helium (stream 1) would be sent into the compressor for the next circulation.

The bottoming cycle could be divided into three sections: the refrigeration subcycle (stream 11–15), the power subcycle (stream 17–23) and the ammonia concentration and flow regulating subsystem (stream 8–10, stream 15–17, stream 24–29).

The flow regulating subsystem includes splitting and absorption units (SPL1, SPL2, ABS1, ABS2, ABS3), both the mass flow rates of the working fluids and their ammonia concentrations could be adjusted to meet the different concentrations requirements in