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Power conversion system considerations for a high efficiency small modular nuclear gas turbine combined cycle power plant concept (NGTCC)

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HIGHLIGHTS

- Nuclear plant concept with very high temperature helium cooled reactor heat source.
- Helium gas turbine and supercritical steam turbine power conversion system.
- Modular plant concept power 180 MWe and projected efficiency 51.5 percent.
- Cogeneration option with electrical power plus steam supply for industrial users.
- Existing technology bases for reactor, gas and steam turbines, and steam generator.

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ABSTRACT

The power conversion system (PCS) in the proposed small modular combined cycle nuclear gas turbine plant is based on the coupling of a non-intercooled topping helium Brayton direct closed-cycle gas turbine and a single-reheat supercritical steam Rankine bottoming cycle. The nuclear heat source (with a thermal rating of 350 MWt) is a helium cooled and graphite moderated very high temperature reactor (VHTR) embodying an assembly of prismatic fuel elements. Based on a reactor outlet (and gas turbine inlet) temperature of 95 °C, the module electrical power output is 180 MWe (50 and 130 MWe from the gas and steam turbines respectively) with an estimated plant efficiency of 51.5 percent. The design and development of the proposed nuclear gas turbine combined cycle (NGTCC) concept would benefit from established technology bases. With the inclusion of a process heat extraction module embodying a compact steam-to-steam re-boiler the proposed plant concept could operate in a cogeneration mode, namely generating electrical power plus providing a supply of uncontaminated process steam to various industrial users. This paper addresses projected HTR to VHTR plant evolution, thermodynamic cycle selection, plant performance, tentative arrangement of the combined cycle PCS, component design considerations and their technology bases, and major development requirements. The NGTCC is an advanced long-term helium cooled reactor concept, and a single module demonstration plant may be realizable by say circa 2030, this leading to commercial operation of multi-module plants, and paving the way for future very high temperature nuclear process heat plants in the middle decades of the 21st century.

1. Introduction

Following the proposal in 1979 by German researchers [1,2] of a modular high temperature helium cooled reactor, with the major components installed in steel pressure vessels, and embodying passive decay heat removal and inherent safety features, many plant design studies have been undertaken worldwide on steam cycle concepts, and later on gas turbine and high temperature process heat plant variants. After the utility operated FSV and THTR commercial power plants in the 1980s, with steam turbine power conversion systems (demonstrating plant efficiencies of about 39 percent), no further commercial HTR plants have operated.

It is encouraging that construction is underway in China on the Shidaowan HTR-PM 500 MWt (200 MWe) pebble bed reactor demonstration steam cycle helium cooled nuclear power plant in

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Abbreviations and nomenclature

A	turbomachine annulus flow area
ANTARES	combined cycle nuclear gas turbine
AN^2	blade root stress parameter
AVR	arbeitsgmeinschaft versuchsreaktor
CC	combined cycle
FSV	Fort St Vrain HTGR plant
GA	general atomics
GT	gas turbine
GTCC	gas turbine combined cycle
GT-MHR	gas turbine modular helium reactor
GTHTR300	JAEA nuclear gas turbine concept
HHT	high temperature helium turbine
HHV	helium turbine test facility
HP	high pressure
HTGR	high temperature gas cooled reactor
HTR	high temperature reactor
HTR-SC	steam cycle plant
HTR-SCC	steam cycle cogeneration plant
ICR	intercooled and recuperated cycle
IHX	intermediate heat exchanger
IP	intermediate pressure
JAEA	Japanese atomic energy agency
Kg	kilogram
MHI	Mitsubishi heavy industries
MHR	modular helium reactor
MPa	mega pascal
MW	megawatt
N	rotational speed, rpm
NGNP	next generation nuclear plant
NGT	nuclear gas turbine
NGTCC	combined cycle nuclear gas turbine
NHS	nuclear heat source
PBMR	pebble bed modular reactor
PBR	pebble bed reactor
PCHE	printed circuit heat exchanger
PCS	power conversion system
PHEM	process heat extraction module
RC	recuperated cycle
ROT	reactor outlet temperature
SG	steam generator
SMR	small modular reactor
ST	steam turbine
THTR	thorium high temperature reactor
TIT	turbine inlet temperature
TZM	tungsten zirconium molybdenum
UHTREX	ultra high temp reactor experiment
VHTR	very high temperature reactor
ZrC	zirconium carbide

Rongcheng City in the Province of Shangcheng, and expected to begin operating in 2017 [3].

Within the U.S. nuclear industry there is growing interest in small modular reactors, and in the near-term demand for electrical power could be met with small steam cycle cogeneration plants based on established HTR technology with a reactor helium outlet temperature of 750 °C.Such a small helium cooled nuclear plant concept has been proposed by JAEA [4]. Embodying prismatic fuel elements the proposed HTR 50S concept, with a thermal rating of 50 MWt, is being designed for electrical power generation, (17.2 MWe with an efficiency of 34 percent), and cogeneration of process steam for industrial uses and district heating.

The NGTCC concept proposed in this paper is viewed as a long-term cogeneration endeavor, with the goal of electrical power generation plus providing a supply of process steam to various industrial users, but with an efficiency of over 50 percent, achievable by the selection of a combined (gas and steam turbine) cycle with a higher reactor helium outlet temperature.

Based on an annular prismatic core rated at 350 MWt with a reactor outlet (and gas turbine inlet) temperature of 950 °C, the estimated power output from the plant module is 180 MWe, this being made up of 50 MWe from the non-intercooled topping helium gas turbine and 130 MWe from the supercritical bottoming steam turbine, giving an estimated plant efficiency of 51.5 percent. In addition to the high efficiency potential, a perceived merit of the combined cycle power conversion system is that it eliminates the need for ultra compact and very complex high cost heat exchangers (including an IHX, recuperator, intercooler and precooler) and a helium circulator that are needed in other gas cooled plants.

The design and development of the proposed NGTCC plant concept would benefit from formidable existing technology bases, these including the following; 1) experience from the two VHTR plants (i.e. AVR in Germany and HTTR in Japan) that have operated successfully for an extended period of time with a reactor outlet temperature of 950 °C, 2) experience gained from the operation of more than 20 closed-cycle gas turbine plants in Europe, and large helium turbomachines used in a utility operated power and heat plant, and in test facilities in Germany, 3) technology transfer (including aerothermal and mechanical design) from aeroengines and high efficiency industrial gas turbines operating with temperatures of 1600 °C, 4) experience gained from the more than 400 supercritical steam turbine plants operating worldwide, and 5) experience gained from the fabrication and operation of once-through flow helical bundle reheat types of steam generators that were used in the two commercial size utility operated HTR power plants (FSV in the USA and THTR in Germany).

The NHS is only briefly described in this paper, since the primary focus is on the PCS, and this includes various aspects of the thermodynamic cycle, major component design features and their technology bases, and development requirements. To be in concert with future energy needs, a process heat extraction module (embodying a steam-to-steam reboiler) is included in a secondary system to facilitate operation in a cogeneration mode, namely to generate electrical power and supply process steam to industrial users.

The proposed NGTCC plant concept essentially evolved from an earlier cogeneration variant [5], and in addition to being more innovative (and with higher efficiency potential) eliminates some of the earlier concerns (e.g. viability of the complex multi-module ultra compact IHX, and the licensing concern of having the gas turbine drive shaft penetrating the primary system pressure boundary). In addition, decoupling the GT and ST drive trains enables the rotational speed of the gas turbine to be increased (from 3600 to 6000 rpm), this contributing to a more optimum low pressure ratio 50MWe helium turbomachine design, with major features, size, and number of compressor and turbine stages etc., that bear a closer resemblance to existing industrial combustion gas turbines used for electrical power generation.

Analytical and design work is in progress on several emerging and innovative SMR concepts with different types of nuclear reactor cores and coolants, however in today's climate of limited technical staff, increased financial restrain, and higher priorities,