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A system analysis tool with a 2D gas turbine modeling for the load transients of HTGRS

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ABSTRACT

This paper presents the operational performance and transient response of a high temperature gas-cooled reactor (HTGR) with an emphasis on the gas turbine through a two-dimensional approach. For its operational and transient simulation we use a GAMMA-T in which the system code, GAMMA, is coupled with the two-dimensional turbomachinery model. We also implement several models into the GAMMA-T: the reactor kinetics model, the bypass valve model, and the models of the core, the heat exchangers, the gas turbine, and the piping. The estimations of compressor and turbine performances are based on a two-dimensional axisymmetric throughflow method that is capable of predicting both the transient and steady-state behavior of the power conversion system (PCS). To demonstrate the code capability, we investigated the two representative transients of GTHTR300, which is a 600 MW direct cycle helium cooled reactor consisting of a prismatic block type core, a horizontal single-shaft configuration of turbomachinery, a recuperator, and a precooler: a loss of heat rejection transient corresponding to the failure of the precooler water supply, and a 30% load reduction transient from nominal operation with bypass control. The simulation results demonstrated the controllability and operational stability for the plant.

1. Introduction

High temperature gas-cooled reactor (HTGR) designs have advantages in energy conversion efficiency mainly due to the closed Brayton cycle. The power conversion system (PCS) based on the direct helium turbine cycle is considered a promising choice because of its simplicity and high efficiency. In this configuration, the gas turbine performance in normal and off-design conditions has a major effect on the dynamic plant behavior. System analysis codes therefore need advanced capabilities for predicting the thermal-hydraulic behavior of the HTGR regarding the close connection between the gas turbine and the other components of the cycle.

The dynamic analysis of closed cycle gas turbine plants dates back to the 1970s. The earlier integrated models used conventional turbomachinery performance maps to predict the control behavior of plants (Bammert and Krey, 1971; Hewing and Forster, 1977; Bardia, 1980; Yan, 1990; Kullmann and Dams, 1996). The recent transient system codes were built with a fine description of the PCS components, but the turbomachinery models were still defined with their performance characteristic maps (Verkerk and Kikstra, 2003; Tauveron et al., 2005). They reported that the off-design conditions could lead to appreciable errors due to limitations of the use of turbomachinery performance maps. Fisher et al. (2005) implemented a compressor model in the RELAP5-3D code, which also required the performance curves. Several studies have been made on accidental situations. In the event of a turbine deblading accident, a thermal-hydraulic study was performed using turbomachinery performance maps (Saez et al., 2006). Focusing on the post-surge and depressurization behavior, Tauveron et al. (2007) applied a one-dimensional axisymmetric turbomachinery model.

Studies to investigate the HTGR behavior under extreme off-design operations have made noticeable progress. On the other hand, little attention has been paid to the development of a more detailed axial turbomachinery model for the transient analysis of PCS than the one-dimensional approach. For practical applications, more precise models are needed because the real flow in an axial-flow multi-stage gas turbine is inherently three-dimensional and exceedingly complex. It is necessary to simplify the flow as having an intermediate level of sophistication while considering the radial pressure gradient due to the lengthwise change of the streamline curvature radius in the gas turbine. Therefore, we have suggested a two-dimensional axisymmetric throughflow calculation to describe the axial turbomachinery in the PCS and incorporated the throughflow calculation tool into a transient system analysis code.

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Nomenclature

A_{valve}	bypass valve cross-sectional area (m^2)
b	blade blockage factor
C_i	concentration of the delayed precursors of group i
h	enthalpy (J/kg)
I	moment of inertia (kg/m^2), iodine concentration
K_P	proportional gain for PI-control
L	lift fraction of the bypass valve
m	meridional direction
$\dot{m}$	mass flow rate (kg/s)
$\dot{P}$	thermal power (W)
$\dot{P}_{shaft}$	shaft power (W)
$\dot{Q}_{Rx}$	reactor thermal power (W)
q	distance in the quasi-orthogonal direction (m)
r	streamline position on the quasi-orthogonals (m)
r_c	radius of streamline curvature (m)
s	entropy (J/kg K)
T	temperature (K)
t	time (s)
V	velocity of the working fluid in turbomachines (m/s)
Xe	xenon concentration

Greek letters

Λ	effective prompt neutron lifetime (s)
α	angle between quasi-orthogonal and streamline (°)
β	fraction of delayed neutrons
γ	fission yield
η_e	generator conversion efficiency
η_m	mechanical efficiency
$\eta_{overall}$	overall plant efficiency
λ	decay constant
θ	circumferential direction
ρ	fluid density (kg/m^3), reactivity
σ_a	microscopic neutron absorption cross-section (m^{-1})
τ	integral time constant for PI-control
ω	rotational speed (rad/s)
Σ_f	macroscopic neutron fission cross-section of the fuel (m^{-1})
Σ_a	macroscopic neutron absorption cross-section (m^{-1})

Subscripts

0	stagnation property, initial
bypass	bypass valve
C	compressor
c_rod	control rod
G	generator
I	iodine
i	precursor group
m	meridional component
Rx_ex	reactor exit
T	turbine
Xe	xenon

Superscripts

*	relative value

Very few attempts have been made at the dynamic analysis of the plant through the two-dimensional axisymmetric turbomachinery model. In this paper, the design of the GTHTR300 by JAEA (Takizuka et al., 2004) is chosen for modeling and analysis. The GTHTR300 is a 600 MW direct cycle helium cooled reactor consisting of a prismatic block type core, a horizontal single-shaft configuration of turbomachinery, a recuperator, a precooler, and the piping. The dynamic models in the GAMMA-T code are described herein, and the operational performance and the representative transient response behavior are presented with a complete description of the modeling of each PCS component. Two transient thermal-hydraulic simulations are carried out for the plant:

(a) the loss of heat rejection without a gas turbine trip;
(b) a 30% load reduction with a bypass valve control.

Table 1
GTHTR300 compressor specifications of the KAIST simulation.

Mass flow rate (kg/s)	449.7
Inlet temperature (°C)	28
Inlet pressure (MPa)	3.52
Pressure ratio	2.00
Hub diameter (mm)	1500
Tip diameter (1st/20th stage) (mm)	1704/1645
Hub-to-tip ratio (1st/20th stage) (mm)	0.880/0.912
Number of stages	20
Rotational speed (rpm)	3600
Number of rotor/stator blades (1st stage)	72/94
Rotor/stator blade chord length (1st stage) (mm)	78/60
Rotor/stator blade height (1st stage) (mm)	102/101
Polytropic efficiency (%)	90.5

2. GAMMA-T code

Under the ROK/US International Nuclear Energy Research Initiative (I-NERI) project, the GAMMA code was originally developed for analyzing the air-ingress phenomena in HTGRs (Lim and NO, 2004; Lim and NO, 2006; Oh et al., 2006; NO et al., 2007a). On the basis of the thermal fluid characteristics of HTGRs, we incorporated the following code requirements into the GAMMA code: the fluid transport and material properties, the multidimensional heat conduction, the multidimensional fluid flow, the chemical reactions, the multicomponent molecular diffusion, the fluid heat transfer and pressure drop, the heat generation and dissipation, and the radiation heat transfer. The GAMMA code has been validated with the air-ingress experiments of HTTR, a SANA-1 afterheat removal test, and a HTTR RCCS mockup experiment.

Owing to the multidimensional thermal-hydraulic analysis feature, the GAMMA code has extended its capability to the transient analysis of the PCS. Over the past few years, we have developed the GAMMA-T code by implementing a two-dimensional gas turbine tool, called SANA, in the GAMMA code. The GAMMA-T code was adapted to a nuclear helium turbine plant for steady-state analysis (Kim et al., 2008; NO et al., 2007b). In the present study, the designs of reactivity control and turbine bypass control are taken into account to deal with the load transients.

3. Specification and modeling of GTHTR300

This work is focused on a particular concept of a 600 MW direct cycle helium cooled reactor by JAEA. The GTHTR300 employs a regenerative, non-intercooled Brayton cycle with helium working fluid. The whole primary system consists of three modular vessels (the reactor pressure vessel, power conversion vessel, and heat exchanger vessel) and is interconnected through coaxial double piping (Yan et al., 2002). The reactor pressure vessel contains a prismatic type graphite core. A horizontal turbocompressor and a generator are arranged in the power conversion vessel. Tables 1 and 2 represent the major specification of the GTHTR300 gas turbine. The compressor is a 20-stage axial-flow type with a constant hub design. The polytropic efficiency of the