



## Direct implementation of an axial-flow helium gas turbine tool in a system analysis tool for HTGRs

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### ABSTRACT

This study concerns the development of dynamic models for a high-temperature gas-cooled reactor (HTGR) through direct implementation of a gas turbine analysis code with a transient analysis code. We have developed a streamline curvature analysis code based on the Newton–Raphson numerical application (SANA) to analyze the off-design performance of helium gas turbines under conditions of normal operation. The SANA code performs a detailed two-dimensional analysis by means of throughflow calculation with allowances for losses in axial-flow multistage compressors and turbines. To evaluate the performance in the steady-state and load transient of HTGRs, we developed GAMMA-T by implementing SANA in the transient system code, GAMMA, which is a multidimensional, multicomponent analysis tool for HTGRs. The reactor, heat exchangers, and connecting pipes were designed with a one-dimensional thermal-hydraulic model that uses the GAMMA code. We assessed GAMMA-T by comparing its results with the steady-state results of the GTHTR300 of JAEA. We concluded that the results are in good agreement, including the results of the vessel cooling bypass flow and the turbine cooling flow.

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### 1. Introduction

Current high-temperature gas-cooled reactors (HTGRs) are mostly based on a Brayton cycle with helium gas as the working fluid. The thermodynamic performance of axial-flow multistage helium gas turbines is of critical concern because the performance has a major effect on the overall efficiency and transient behavior of HTGRs. Thus, system analysis codes need advanced capabilities for predicting the dynamic behavior of a plant. To deal with the steady-state and transient analysis of HTGRs, gas turbine performance characteristics are required over a wide range of operating conditions.

Conventionally, gas turbine design companies provide off-design performance maps. Recalculated off-design performance maps are needed for accurate transient analysis whenever a gas turbine design is changed for the optimization of the overall design conditions. The gas turbine performance maps are usually implemented in the system analysis code as a series of tables or correlations (Verkerk and Kikstra, 2003). Using these methods, we can see that the potential of interpolation errors is due to the non-linearity in the efficiency curves (Fisher et al., 2005).

Although the design of modern turbomachinery relies heavily on CFD, the task of performing full calculations for a three-dimensional flow in a multistage gas turbine is too time-consuming for routine analysis (Horlock and Denton, 2005). Thus, the CFD method is unsuitable for predicting of a long transient of a power conversion system (PCS). Tauveron et al. (2007) developed a one-dimensional approach by solving Navier–Stokes equations as a simplification of a complex three-dimensional flow to describe the compressor and turbine behavior. The streamlines change radii along the stages in a typical multistage axial-flow gas turbine, and this lengthwise change in radius creates an additional pressure gradient that acts on the flow (Korakianitis and Zou, 1992). The one-dimensional axisymmetric approach can be used for preliminary considerations of the compressor or turbine; however, it does not take into effect this additional pressure gradient from the streamwise change of the streamline curvature. On the other hand, a two-dimensional throughflow calculation is simplified to a suitable level of sophistication and this approach takes account of the radial pressure gradient of real flows in gas turbines. The throughflow analysis method can deal with multistage gas turbines and provide enough reliable information to enable us to proceed with simple and effective changes to the design within a short time scale; it is known that CPU time of the throughflow analysis is a few seconds using a typical PC. Furthermore, the code can be coupled with

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**Nomenclature**

$a_{sf}$	specific solid-to-fluid interfacial area [ $m^{-1}$ ]
$A$	cross-sectional area [ $m^2$ ]
$b$	blade blockage factor
$B$	additional body force
$C_F$	drag coefficient in a pebble bed
$C_p$	specific heat capacity [ $J/kg K$ ]
$D_{eq}$	equivalent diffusion ratio
$g$	gravity constant [ $m/s^2$ ]
$h$	enthalpy [ $J/kg$ ]
$h_{sf}$	interfacial heat transfer coefficient [ $W/m^2 K$ ]
$I$	moment of inertia [ $kg/m^2$ ]
$J$	total molecular diffusion flux [ $kg/m^2 s$ ]
$J$	diffusion flux with respect to mass average velocity [ $kg/m^2 s$ ]
$k$	mass transfer coefficient [ $m/s$ ]
$K$	permeability
$m$	meridional direction
$\dot{m}$	mass flow rate [ $kg/s$ ]
$p$	pressure [MPa]
$\dot{P}_{shaft}$	shaft power [W]
$q$	distance in the quasi-orthogonal direction [m], heat flux [ $W/m^2$ ]
$\dot{q}'''$	volumetric heat source [ $W/m^3$ ]
$r$	streamline position on the quasi-orthogonals [m]
$r_c$	radius of streamline curvature [m]
$R$	generation/dispersion of gas species by chemical reaction [ $kg/m^3 s$ ]
$s$	entropy [ $J/kg K$ ]
SM	surge margin for compressors
$t$	time [s]
$T$	temperature [K]
$u$	mass average velocity of fluid
$U$	rotor speed [ $m/s^2$ ]
$V$	fluid absolute velocity or mass average velocity [ $m/s$ ]
Vol	volume of a scalar cell
$W$	fluid relative velocity [ $m/s^2$ ]
$W_s$	molar weight of gas species
$Y_s$	mass fraction of gas species
$z$	axial direction, axial distance [m]

**Greek symbols**

$\alpha$	angle between quasi-orthogonal and streamline [ $^\circ$ ], absolute flow angle [ $^\circ$ ]
$\beta$	relative flow angle [ $^\circ$ ]
$\eta$	efficiency
$\theta$	circumferential direction
$\lambda$	thermal conductivity [ $W/m K$ ]
$\lambda_{disp}$	thermal conductivity induced by thermal dispersion [ $W/m K$ ]
$\lambda_{eff}$	effective thermal conductivity in a pebble bed [ $W/m K$ ]
$\mu$	fluid viscosity [ $kg/m s$ ]
$\rho$	fluid density [ $kg/m^3$ ]
$(\rho C)_p$	volumetric heat capacity of solid or pebble [ $J/m^3 K$ ]
$\sigma$	solidity of a blade
$\phi$	pitch angle of streamline [ $^\circ$ ]
$\varphi$	porosity
$\omega$	rotational speed [rad/s]

**Subscripts**

0	stagnation property
C	compressor
ch	chemical reaction
design	design-point condition
exit	blade exit
f	fluid
G	generator
inlet	blade inlet
$m$	meridional component, mechanical
p	solid or pebble
s	gas species
sf	solid-to-fluid
surge	surge condition
T	turbine
w	wall
$\infty$	polytropic

**Superscripts**

bulk	bulk
$n$	old time step
$n + 1$	new time step
wall	wall

the system code fairly easily and only a short computation time is needed to run the coupled code for the transient analysis.

We therefore suggest an alternative way of estimating the gas turbine performance in steady-state and transient operations under normal conditions. In this approach, we use a two-dimensional axisymmetric throughflow method for thermodynamic analysis of a flow in helium gas turbines and then model other PCS components one-dimensionally, except for the gas turbines. The SANA code performs a streamline curvature analysis, and the off-design performance of the gas turbine is incorporated into a transient system code by direct implementation. In this study, the implementation of gas turbine performances and the one-dimensional modeling of other PCS components were performed in the GAMMA code (Lim and No, 2006) which was originally developed for the purpose of analyzing postulated accidents in HTGRs. We compared the steady-state simulation results of the open literature data of the JAEA GTHT300 design (Takizuka et al., 2004) because of the detailed information of the gas turbine. The design parameters of the GTHT300 plant are presented in Table 1.

**2. Modeling of axial-flow gas turbines**

We focus on the performance prediction of the axial-flow gas turbine under normal operation. From steady and inviscid flow assumptions, the SANA code evaluates the axial-radial variation of fluid properties in a gas turbine. The continuity,

**Table 1**  
Design parameters of the GTHT300 plant

Reactor thermal power	600 MW
Plant cycle	Brayton cycle without intercooler
Net generating efficiency	45.6%
Helium flow rate	438 kg/s
Reactor inlet temperature	587 °C
Reactor outlet temperature	850 °C
Helium inlet pressure of core	6.92 MPa
Fuel element	Prismatic pin-in-block
Shaft design type	Horizontal, single-shaft
Shaft speed	3600 rpm

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