Coupling of a 2-D Gas Turbine Tool with a System Analysis Code for Predicting the Transient Behavior of the HTGR

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1. Introduction

System analysis codes need advanced capabilities for predicting the transient behavior of the high temperature gas-cooled reactor. The thermodynamic performance of helium gas turbine is of critical concern because the performance has a major effect on the overall efficiency of the HTGR. We developed an improved way of estimating the gas turbine performance of the HTGR in steady-state and transient operations under normal condition [1]. The dynamic models are described herein, and the steady-state and representative transient simulation results are presented.

2. Methods and Results

We focus on the performance prediction of the axial-flow gas turbine under normal operation. The SANA code evaluates the axial-radial variation of fluid properties in the gas turbine. The steady-state and transient analysis of the HTGR is performed by implementing the SANA in the GAMMA code, which was originally developed for safety analysis of HTGR air-ingress [2]. The reactor, heat exchangers, and connecting pipes were designed with a one-dimensional thermal-hydraulic model that uses the GAMMA code.

2.1 SANA Code for Axial-Flow Gas Turbines

The calculation of the flow along the hub-to-tip plane is usually referred to as the throughflow method. From steady and inviscid flow assumptions, the continuity, momentum and energy equations are coupled with the radial-equilibrium conditions to provide a differential equation for the axial component of velocity. We applied the Newton-Raphson numerical logic for the throughflow calculation, which enables the gas turbine code to be directly coupled with the system code: only a short computation time is needed to run the coupled code for the transient analysis with improved numerical stability. This throughflow calculation is linked with empirical loss correlations to predict the gas turbine efficiency. The variations in the gas turbine performance over the operating range of speed and shaft power are referred to as performance characteristics, and the transient behavior of a power conversion system (PCS) is predicted from the knowledge of the performance characteristics.

2.2 Shaft System Modeling in GAMMA-T Code

For a single-shaft design, the compressor and generator are driven directly by the turbine. We assume that the generator consumes the excessive power of the turbo-compressor shaft. Accordingly, the rotational speed of the turbo compressor can be set to the nominal speed. Considering the mechanical loss, the turbine power needed to maintain the constant shaft speed is

$$\dot{P}_{shaft,G} = \eta_m \dot{P}_{shaft,T} - \dot{P}_{shaft,C} \quad (1)$$

where the transmission efficiency is denoted by η_m.

2.3 Thermal-Hydraulic Modeling for PCS Components in GAMMA-T Code

The reactor was modeled by using the parallel one-dimensional elements of the fluid block associated with the TRISO matrix wall blocks. The thermal power of the reactor is calculated from the point kinetics equations with six groups of delayed precursors. The temperature coefficient of reactivity is adopted from the MGR-GT design [3], and the reactivity by fission product poisoning was given by the simplified decay scheme of Xenon and Iodine. We designed the recuperator and the precooler as single-pass counter-current heat exchangers according to the steady-state requirements of the reference design.

In the semi-implicit numerical scheme, the pressure difference between the inlet and outlet of the gas turbine is implicitly coupled to the velocities through the dependence on the mass flow. By assuming that the pressure change depends on the mass flow rate and by using a first-order Taylor series expansion, we derive the following relation:

$$\Delta p^{n+1} = \Delta p^n + \left(\frac{dp}{d\dot{m}}\right)^n \left(\dot{m}^{n+1} - \dot{m}^n\right) \quad (2)$$

The pressure gradient with respect to the mass flow rate is calculated by the forward difference method of Newton’s difference formula. The energy change between the inlet and outlet of the gas turbine is calculated for the following control volume as the heat source in the energy equation as follows:

$$\frac{\partial}{\partial t}\left(\rho C_p T\right) + \frac{1}{A}\frac{\partial}{\partial z}\left(\rho C_p TAV\right) = Q_w + \frac{1}{A}\frac{\partial \dot{P}_{shaft}}{\partial z} \quad (3)$$

2.4 Steady-State and Transient Analysis

To demonstrate the GAMMA-T code, we applied it to the GTHTR300 design of JAEA [4]. After describing of the non-integrated plant design, we simulated the steady-state of the whole cycle to investigate the performance of the gas turbine and heat exchangers in normal operation. To obtain the steady-state conditions, the precooler outlet temperature is kept constant at 301 K. Fig. 1 shows the nodalization and calculated baseline parameters of each component.

In the following, simulation of loss of heat rejection is performed to investigate the effect on the PCS due to failure of precooler water supply. This is accomplished by making the coolant flow through the precooler very large and adjusting the coolant temperature from 301 K to 373 K. The turbo-compressor rotational speed was set to 3600 rpm because the torque balance of the shaft was maintained by the generator. In Fig. 2, transient behaviors of the PCS are presented after a step-wise increase of the coolant temperature at 120 sec. This leads to fast decrease and gradual recovery of the mass flow rates through the cycle. As shown in Fig. 2 (a), the reactor outlet temperature hardly deviates from its original value because of the rapid feedback from fuel temperature to reactivity. The transient response of the reactor, the heat rejection through the precooler, and the power on the turbo-shaft is presented in Fig. 2 (b). The reactor power oscillation is due to the variation of the mass flow rates through the cycle during the transient.

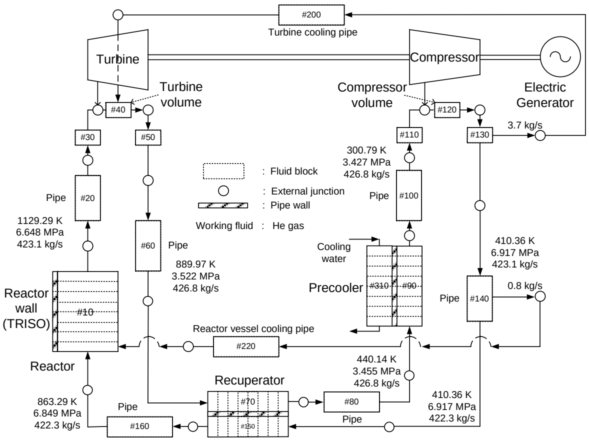

Fig. 1. Steady-state simulation for the GTHTR300 design

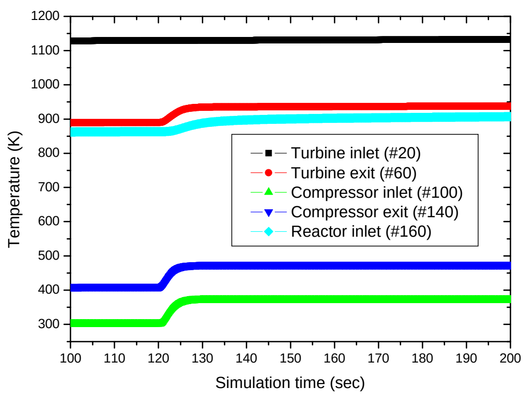

Fig. 2 (a) Behavior of temperature after a step-wise increase of coolant temperature from 301 K to 373 K

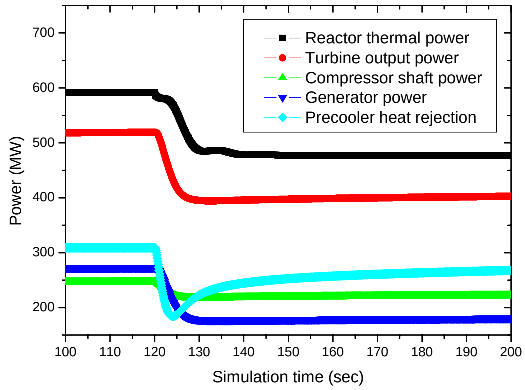

Fig. 2 (b). Behavior of power after a step-wise increase of coolant temperature from 301 K to 373 K

3. Conclusions

This paper presented the turbo-compressor steady-state and transient simulation of a HTGR with helium working fluid in conditions of normal operation. The SANA code was implemented in the GAMMA code, and the capability of two-dimensional modeling of the gas turbine and one-dimensional modeling of the reactor and heat exchangers has been tested successfully. This type of system analysis is able to describe the behavior of the each component in the PCS with reliable information. The models can be advantageous for analysis of transient behavior as well as for design optimization of heat and mass balance of plants.

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