Chinese Journal of Chemical Engineering 23 (2015) 2092–2097

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJChE

Adaptive output-feedback power-level control for modular high temperature gas-cooled reactors

Zhe Dong *

Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China

A R T I C L E   I N F O

Article history:
Received 25 May 2015
Received in revised form 5 June 2015
Accepted 16 June 2015
Available online 29 August 2015

Keywords:
High temperature gas-cooled reactor
Power-level regulation
Adaptive control

A B S T R A C T

Small modular reactors (SMRs) are beneficial in providing electricity power safely and viable for specific applications such as seawater desalination and heat production. Due to its inherent safety feature, the modular high temperature gas-cooled reactor (MHTGR) is considered as one of the best candidates for SMR-based nuclear power plants. Since its dynamics presents high nonlinearity and parameter uncertainty, it is necessary to develop adaptive power-level control, which is beneficial to safe, stable, and efficient operation of MHTGR and is easy to be implemented. In this paper, based on the physically-based control design approach, an adaptive output-feedback power-level control is proposed for MHTGRs. This control can guarantee globally bounded closed-loop stability and has a simple form. Numerical simulation results show the correctness of the theoretical analysis and satisfactory regulation performance of this control.

© 2015 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

1. Introduction

Nuclear fission energy is a crucial type of clean energy and plays an important role in meeting increasing energy demands. Because of its inherent safety feature, the modular high temperature gas-cooled reactor (MHTGR) is considered as one of the best candidates for next generation nuclear power plants. The MHTGR uses helium as coolant and graphite as moderator and structural material, and its safety is given by low power density, strong negative temperature reactivity feedback effect, and slim shape [1]. China began to study MHTGR technique at the end of 1970s, and the first MHTGR, *i.e.* the 10 MW_{th} pebble-bed high temperature gas-cooled test reactor, HTR-10, developed in Tsinghua University passed its first criticality in December 2000 and achieved its full power in January 2003 [2]. Based on the HTR-10, a high temperature gas-cooled reactor pebble-bed module (HTR-PM) project was proposed [3]. The HTR-PM plant consists of two pebble-bed one-zone MHTGRs with a combined 2×250 MW_{th} power, and is designed to be operated in the scheme of two nuclear steam supplying system (NSSS) modules driving one steam turbine. As shown in Fig. 1, the NSSS module is constituted by an MHTGR, a helical coiled once-through steam generator (OTSG), a primary helium blower, and some connecting pipes.

For all power plants, the power supply and demand must be balanced by either generation or load [4], which means that load following ability of a nuclear power plant is needed. Based on the sliding mode control (SMC) method, Shtessel designed a nonlinear power-level control for the space reactor TOPAZ II [5]. Since SMC has an intrinsic

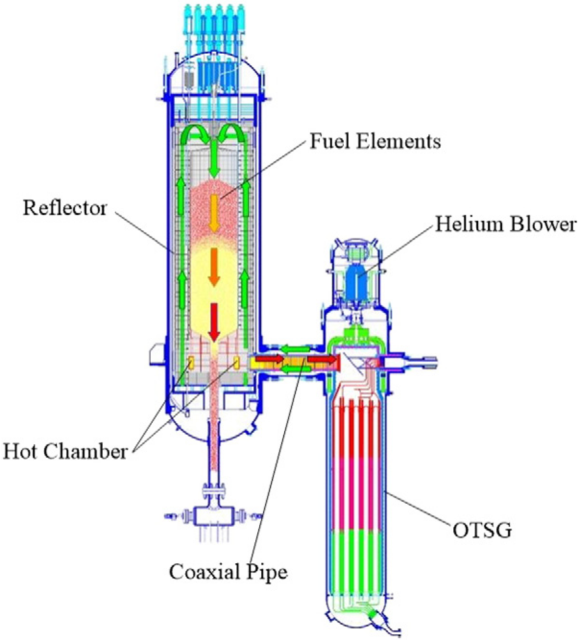

Fig. 1. NSSS of HTR-PM plant.

---

* Corresponding author.
E-mail address: dongzhe@mail.tsinghua.edu.cn.

http://dx.doi.org/10.1016/j.cjche.2015.08.027
1004-9541/© 2015 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

drawback in chattering, recursive SMC method was introduced to the reactor control design and a fuzzy-adapted nonlinear power-level control was designed for advanced boiling water reactors [6]. Model predictive control (MPC) method is an effective way to deal with the system nonlinearity. Na *et al.* introduced the MPC to this field [7] and applied it to design power-level control for pressurized water reactors (PWRs) [8]. For dealing with dynamical nonlinearity better, nonlinear MPC method was applied to power-level control design for PWRs [9, 10]. Based on the technique of iterative damping assignment (IDA), Dong gave a nonlinear feedback power-level control to the MHTGR [11]. Although this IDA-based control can provide globally asymptotic closed-loop stability, its expression is too complex to be implemented practically. Based on the physically-based control design approach whose key idea is to stabilize a physical system by retaining its natural dynamics beneficial to stabilization, Dong proposed a nonlinear dynamic output feedback power-level control for the MHTGR [12]. Then, motivated by the need for dealing with the parameter uncertainty, Dong gave a nonlinear adaptive power-level control for MHTGRs [13]. However, since this control has a dynamic output-feedback structure, it is still complex to be implemented. Therefore, it is necessary to design power-level control for the MHTGR with simple form and strong adaptation ability.

In this study, a novel adaptive output-feedback power-level control for the MHTGR is given. It can be tuned on-line and guarantee globally bounded closed-loop stability. Numerical simulation is carried out to verify the feasibility and show the performance of this new controller.

2. Nonlinear State-Space Model and Problem Formulation

2.1. Nonlinear state-space model for control design

As shown in Fig. 1, the MHTGR and OTSG of the NSSS are arranged side by side and connected to each other by a horizontal coaxial hot gas duct. Cold helium enters the main blower mounted on the top of OTSG and is pressurized before flowing into the cold gas duct. It enters the channels inside the reflector of the core and then passes the pebble-bed from top to bottom where it is heated to a high temperature. Hot helium leaves the hot gas chamber at the bottom of reflector and flows into the primary side of the OTSG through the hot gas duct. The nodalization of the primary loop is shown in Fig. 2.

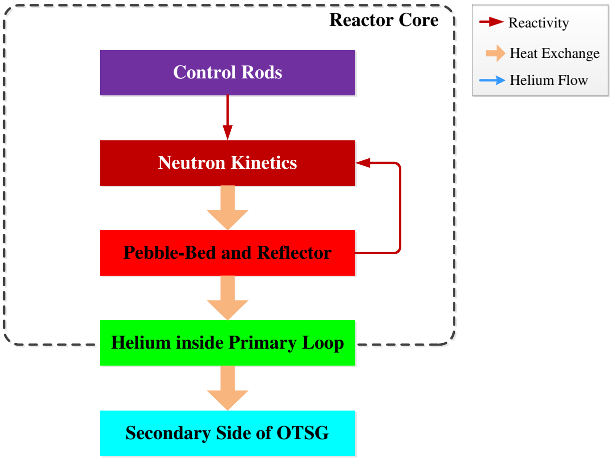

Fig. 2. Nodalization of the primary loop.

By adopting the point kinetics with one equivalent delayed neutron group and with the temperature reactivity feedback effect of the reactor core constituted by the pebble-bed of fuel elements and reflector, the dynamic model for control design can be written as

$$\begin{cases} \dot{n}_\mathrm{r} = \dfrac{\rho_\mathrm{r} - \beta}{\Lambda} n_\mathrm{r} + \dfrac{\beta}{\Lambda} c_\mathrm{r} + \dfrac{\alpha_\mathrm{R}}{\Lambda} n_\mathrm{r} (T_\mathrm{R} - T_\mathrm{R,m}), \\ \dot{c}_\mathrm{r} = \lambda (n_\mathrm{r} - c_\mathrm{r}), \\ \dot{T}_\mathrm{R} = -\dfrac{\Omega_\mathrm{P}}{\mu_\mathrm{R}} (T_\mathrm{R} - T_\mathrm{H}) + \dfrac{P_0}{\mu_\mathrm{R}} n_\mathrm{r}, \\ \dot{T}_\mathrm{H} = \dfrac{\Omega_\mathrm{P}}{\mu_\mathrm{H}} (T_\mathrm{R} - T_\mathrm{H}) - \dfrac{\Omega_\mathrm{S}}{\mu_\mathrm{H}} (T_\mathrm{H} - T_\mathrm{S}), \\ \dot{\rho}_\mathrm{r} = G_\mathrm{r} z_\mathrm{r}, \end{cases} \tag{1}$$

where n_r is the relative neutron power, c_r is the relative concentration of delayed neutron precursor, β is the fraction of the delayed fission neutrons, Λ is the effective prompt neutron life time [s], ρ_r is the reactivity provided by control rods, λ is the effective radioactive decay constant of the precursor [s^{-1}], T_R and α_R are the temperature [°C] and reactivity feedback coefficient [$°\mathrm{C}^{-1}$] of the reactor core, $T_\mathrm{R,m}$ is the initial equilibrium value of T_R, P_0 is the rated thermal power [W], T_H is the average temperature of the primary helium flow, T_S is the secondary average coolant temperature of OTSG, Ω_P is the heat transfer coefficient between helium flow and reactor core [$\mathrm{W} \cdot °\mathrm{C}^{-1}$], Ω_S is the heat transfer coefficient between the two sides of OTSG, μ_R and μ_H are the total heat capacities of reactor core and helium inside the primary loop [$\mathrm{J} \cdot °\mathrm{C}^{-1}$], respectively, G_r is the total differential reactivity of the control rod, and z_r is the rod speed signal given by the designed power-level control [$\mathrm{m} \cdot \mathrm{s}^{-1}$]. Here, it is noted that α_R is guaranteed to be negative by MHTGR physical design.

Define the deviations of the actual values of n_r, c_r, T_R, T_H, T_S, and ρ_r from their equilibrium values, *i.e.* n_r0, c_r0, T_R0, T_H0, and ρ_r0, as $\delta n_\mathrm{r} = n_\mathrm{r} - n_\mathrm{r0}$, $\delta c_\mathrm{r} = c_\mathrm{r} - c_\mathrm{r0}$, $\delta T_\mathrm{R} = T_\mathrm{R} - T_\mathrm{R0}$, $\delta T_\mathrm{H} = T_\mathrm{H} - T_\mathrm{H0}$, $\delta T_\mathrm{S} = T_\mathrm{S} - T_\mathrm{S0}$, and $\delta \rho_\mathrm{r} = \rho_\mathrm{r} - \rho_\mathrm{r0}$. Since δT_S reflects the influence of the secondary to the primary loop and can be well suppressed by adjusting the flow rate of OTSG feed water, its influence is omitted in this paper. Moreover, let

$$\boldsymbol{x} = [x_1 \quad x_2 \quad x_3 \quad x_4]^\mathrm{T} = [\delta n_\mathrm{r} \quad \delta c_\mathrm{r} \quad \delta T_\mathrm{R} \quad \delta T_\mathrm{H}]^\mathrm{T} \tag{2}$$

$$\xi = \delta \rho_\mathrm{r} \tag{3}$$

and

$$u = G_\mathrm{r} z_\mathrm{r} \tag{4}$$

where $\boldsymbol{x}$ is called the state-vector of the MHTGR.

Then, the nonlinear state-space model for the power-level control design can be written as

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x}) \xi, \\ \dot{\xi} = u, \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}), \end{cases} \tag{5}$$

where

$$\boldsymbol{f}(\boldsymbol{x}) = \begin{bmatrix} -\dfrac{\beta}{\Lambda}(x_1 - x_2) + \dfrac{\alpha_\mathrm{R}}{\Lambda}(n_\mathrm{r0} + x_1) x_3 \\ \lambda (x_1 - x_2) \\ \dfrac{P_0}{\mu_\mathrm{R}} x_1 - \dfrac{\Omega_\mathrm{P}}{\mu_\mathrm{R}} (x_3 - x_4) \\ \dfrac{\Omega_\mathrm{P}}{\mu_\mathrm{H}} (x_3 - x_4) - \dfrac{\Omega_\mathrm{S}}{\mu_\mathrm{H}} x_4 \end{bmatrix} \tag{6}$$

$$\boldsymbol{g}(\boldsymbol{x}) = \begin{bmatrix} \dfrac{n_\mathrm{r0} + x_1}{\Lambda} & \boldsymbol{O}_{1 \times 3} \end{bmatrix}^\mathrm{T} \tag{7}$$

Download English Version:

https://daneshyari.com/en/article/166341

Download Persian Version:

https://daneshyari.com/article/166341

Daneshyari.com