Annals of Nuclear Energy 75 (2015) 658–664

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Operation characteristic of Integrated Pressurized Water Reactor under coordination control scheme

Xue Du [a], Genglei Xia [b,*], Lihui He [c]

[a] College of Automation, Harbin Engineering University, Harbin, China
[b] Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, China
[c] College of Computer Science and Information Technology, Harbin Normal University, Harbin, China

ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 28 August 2014
Accepted 31 August 2014
Available online 26 September 2014

Keywords:
OTSG
Coordination control scheme
RELAP5 code
Operation boundary

ABSTRACT

Once-Through Steam Generator (OTSG) with smaller size and larger heat transfer capability, is typically used for Small and Medium sized Reactors (SMRs). Because the Integrated Pressurized Water Reactor (IPWR) uses OTSG, the feed water is heated to superheated steam by primary coolant, and the higher steam temperature could improve the thermal efficiency of the reactor power plant. However, the smaller size and heat capacity make stable operation more difficult. In this paper, a mathematical model of IPWR is established using RELAP5 code, and a coordination control scheme is used to study the rapid load following characteristics of OTSG. The effects of main operating parameters related to stable operation of OTSG are investigated. Average coolant temperature, steam pressure and OTSG grouping run operation boundary are confirmed. This operation boundary can be used to design and optimize the control system.

1. Introduction

Once-Through Steam Generator (OTSG) has some particular features including smaller size, faster response, and stronger load following capacity. It is widely used in Integrated Pressurized Water Reactor (IPWR) due to its perfect performance and compact structure (Carelli et al., 2004; Bae et al., 2001; Fukami and Santecchia, 2000; Hibi et al., 2004). For casing once-through steam generator (COTSG), primary coolant flows inside both the inner tube and shell side, secondary fluid flows in the annular channel, and subcooled water is heated to superheated steam by primary coolant. The higher steam temperature could improve the thermal efficiency of reactor power plant.

COTSG with smaller size and larger heat transfer capability draws more and more attention in recent years. Many researchers have investigated the heat transfer characteristics of narrow annuli channel (Kang et al., 2001; Zarate et al., 2001; Lu and Wang, 2008), and same researches aiming at the flow distribution of primary side (Zeng et al., 2007; Wei et al., 2011). These related studies indicate that the heat transfer characteristics of narrow annuli are different from conventional channels. OTSG could improve the thermal efficiency of nuclear power plants, but the intense phase change process in OTSG secondary side leads to two-phase flow instability at low load conditions. The smaller size and heat capacity make it more difficult to stabilize operation.

For IPWR system, larger parameter change can produce higher thermal shock and serious fatigue damage during the transient response process. Therefore, the performance of control system for OTSG is demanded urgently to prevent drastic change of system parameters. Many scholars have conducted a lot of research work (Kusunoki et al., 2000; Fausto and Bojan, 2008; Kang and Park, 2008). Hu et al. utilized a coordination control system to implement the rapid load following (Hu et al., 2012). Liu et al. adopted a load following control mode to constant the primary coolant average temperature and the secondary steam pressure, the reactor power automatically adjusts to match with the steam flow (LIU et al., 2010). These research results have demonstrated the effectiveness of OTSG coordination control system, but failed to take the detailed analysis of steady-state and transient operating characteristics for IPWR system.

In this paper, a mathematical model of the integrated reactor is established using RELAP5 code. And a coordination control scheme is designed to achieve the precise control of reactor power. Using the established model, the operating characteristics of OTSG under steady-state and transient condition are investigated. Finally, the effects of main operating parameters related to stable operation of OTSG are investigated, which could be meaningful to the design and operation of the control system.

* Corresponding author. Tel.: +86 0451 82569302; fax: +86 0451 82569622.
E-mail address: xiagenglei@163.com (G. Xia).

http://dx.doi.org/10.1016/j.anucene.2014.08.066
0306-4549/

2. Research model

2.1. RELAP5 model of IPWR

The major design parameters of IP200 (Integrated Pressurized Water Reactor with 220 MW thermal power output) reactor are shown in Table 1 (Salah et al., 2013). Compared with conventional nuclear power plant, the IPWR has much smaller size and higher inherent safety. For integrated reactor, the main components, such as steam generator, pressurizer, reactor core and main pump, are contained within the pressure vessel.

In order to study the operating characteristics of OTSG, RELAP5 code is used to establish the reactor system model. RELAP5 code is the best-estimate system analysis code based on a two-fluid model for two-phase flows (INEL, 1998). The nodalization of IPWR is shown in Fig. 1.

2.2. Coordination control scheme

The schematic diagram of the control system for IPWR is shown in Fig. 2. Reactor power control system and secondary feed-water control system compose the ideal steady-state control scheme. And the two subsystems influence each other through OTSG. For this ideal steady-state control scheme, the important parameters are primary average coolant temperature (T_{av}) and steam pressure (P_s). The control system should remain these two parameters stable as the plant load varies (Liu et al., 2010; Peng, 2005). The reactor power is controlled by the control rods to ensure the primary coolant average temperature stable. The feed-water control system adjusts the feedwater flow to keep the steam pressure steady.

Reactor target power is calculated as follows:

$$n_0 = k_1 G_s + k_2 \left(\Delta T_{av} + \frac{1}{\tau} \int_0^t \Delta T_{av} dt \right) \quad (1)$$

$$\Delta T_{av} = T_{av} - T_{av,0} \quad (2)$$

Target feedwater flow rate is calculated as follows:

$$G_{w,0} = k_3 G_s + k_4 \left(\Delta P_s + \frac{1}{\varepsilon} \int_0^t \Delta P_s dt \right) \quad (3)$$

$$\Delta P_s = P_s - P_{s,0} \quad (4)$$

where k_1, k_2, k_3, k_4 are the corresponding proportion coefficients, and τ, ε are the corresponding integral coefficients.

3. Results and discussion

3.1. Steady state characteristics of OTSG

The temperature distribution along heat transfer tube at 100% FP (Full Power) condition is shown in Fig. 3. Due to the fact that the flow area of shell side is larger than inner tube, the mass flow rate in shell side is bigger, so did the coolant temperature. The figure shows that flow region of secondary side could be divided into three sections including subcooled region, two phase region and steam region. The fluid in subcooled region is single-phase water whose temperature increases gradually in the process of upward flowing. Then saturation water keeps evaporating in two phase region. Finally subcooled water is heated to superheat steam and flows out of OTSG.

The secondary side fluid temperature distribution along heat transfer tube at different load conditions is shown in Fig. 4. The figure illustrates that the length of subcooled region and two phase region shorten while superheat steam region get lengthen with load reducing. According to the ideal steady-state operation program, the coolant average temperature remains constant as the load varies. Thus feed-water is heated to superheat state quickly at low flow condition. Because of the single-phase water resistance decreasing, the intense phase change process in OTSG secondary side may lead to two-phase flow instability. Therefore it is necessary to set the minimum feed water flow to ensure the stability of OTSG.

Table 1
Design parameters of IP200.

Parameter	Value
Initial core power (100% of nominal)	220.0 MW
Core inlet temperature	285.0 °C
Core outlet temperature	324.0 °C
Pressurizer pressure	15.5 MPa
Primary coolant flow rates	1200.0 kg/s
Initial feed water flow rate	90.0 kg/s
Main feed-water temperature	100.0 °C
Main steam pressure	3.0 MPa
Superheat of steam	40.0 °C

Secondary fluid undergoes a dramatic phase transformation from subcooled water to superheated steam, and the heat absorption curves under different load conditions are displayed respectively in Fig. 5. In subcooled region, as the single phase water temperature increases, the heat-exchange decreases with height of OTSG secondary side increasing. In the saturated boiling region, bubble adds disturbance which increases local flow velocity and secondary fluid absorbs more thermal power with void fraction adding. Fluid in superheated steam region is single-phase steam and absorbs less heat with steam temperature increasing. Since the convective heat transfer coefficient of steam is far less than single-phase water, the heat transfer amount in superheated steam region is the least.

Due to the change of heat-exchange in different regions, the transformation of secondary heat transfer region impacts primary coolant temperature strongly. The temperature variation along heat transfer tube demonstrates in Fig. 6. In single-phase water region and two-phase boiling region, primary coolant temperature reduces generously. The coolant temperature in superheated steam region appears relative smooth change.

The variation of primary coolant average temperature and secondary steam temperature under different load conditions are shown in Fig. 7. Reactor core outlet temperature decreases and inlet temperature increases with the reducing of reactor power. The difference between outlet and inlet temperature declines to ensure bringing the reactor power out. On the condition of 20% FP, primary average temperature maintains at 573.15 K, whereas temperature difference is only 6.56 °C. On the other side, as the length of superheat steam region increases (Fig. 3), the steam temperature rises at low load condition.

Control system considers the demand of steam as the main object. Secondary steam pressure is controlled by adjusting feed-water flow, and the reactor power is controlled by the control rods to realize the coolant average temperature constant. Relying on the coordinated control between primary loop and secondary loop, the steam flow is achieved to meet the requirements. The ratio of steam flow, feed water flow and reactor power under different load conditions display in Table 2. The steam flow is corresponding to the secondary load. In the process of transforming into superheat steam from subcooled water, steam volume expansion could cause OTSG outlet steam pressure increasing.

Under low load condition, the heat absorption of secondary side water increases with the length increasing of superheated steam region. A relatively higher reactor power is required to ensure the constant of primary coolant average temperature. In Fig. 8,