Progress in Nuclear Energy 71 (2014) 179–187

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Modeling and control strategy of the China accelerator driven subcritical reactor

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ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form
15 November 2013
Accepted 21 November 2013

Keywords:
Accelerator driven subcritical reactor
Zero-dimensional model
Control strategy
Simulation.

ABSTRACT

To investigate the dynamic and control characteristics of the CLEAR-IB plant, a new lead bismuth eutectic (LBE)-cooled Accelerator Driven Subcritical reactor, a model for the main components of the reactor and the most relevant interactions among them are developed. The system is comprised of the primary cooling circuit with LBE, the secondary cooling circuit with water and the associated air cooling system for an effective rejection of thermal power to the environment as a final heat sink. A Proportional-Integral (PI) controller is designed to keep the power following the set value as quickly as possible. To keep the coolant temperature at the inlet of the core constant, a control strategy based on a simultaneous feed-forward and feedback scheme has been adopted. Based on the developed model and control strategy, dynamic simulation of the whole system with controllers in the case of a load step change is performed. The simulation results show that the proposed model is sufficiently accurate to describe the dynamic behaviors of the plant in spite of its simplicity and the developed controllers for the CLEAR-IB can provide superior reactor control capabilities due to the efficiency of the control strategy adopted.

1. Introduction

An accelerator driven system (ADS) known as CLEAR-IB is under investigation for its transmutation potential of long-lived nuclear waste in China. The CLEAR-I is a single system to be operated in two modes. As the accelerator's performance can't meet requirement now, a critical system (CLEAR-IA) was planned to be built firstly and leave room in the central of the core for the accelerator. The subcritical system (CLEAR-IB) will be built when the accelerator has a better performance. As shown in Fig. 1, the CLEAR-IB plant is a subcritical reactor, combining a lead bismuth eutectic (LBE)-cooled fast reactor with a high-energy external proton source.

The control characteristics and operation strategies of the CLEAR-IB are significantly different from those of the traditional Pressurized Water Reactors (PWRs) because of the variances in coolant properties as well as major differences due to the operation in the fast versus the thermal neutron spectrum. Thus, a proper dynamic model is needed for control system design and simulation of the CLEAR-IB. Large scale three-dimensional dynamic models used in commercial softwares are sufficiently accurate for equipment design, safety assessment, and operator training. However, these models and computer codes are too much detailed for operation research and control system design because they are of too high degree and their structures do not allow us to design model-based controllers directly on them. To investigate the dynamic characteristics of the CLEAR-IB reactor for control system design and simulation, a simplified dynamic model is preferred here. Thus, the lumped parameter dynamic modeling method is employed in this paper to study the dynamic and control characteristics of the CLEAR-IB. Such models are based upon extremely coarse lumping of mass, energy and momentum balances. These lumped parameter models are typically described by ordinary differential equations, which focus on the fast simulation and the control system design of the reactor.

The rest of the paper is organized in the following sequence. Section 2 gives a brief description of the CLEAR-IB plant. Section 3 describes the modeling methodology and the mathematical formulation of the plant. Section 4 presents the control strategy and

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http://dx.doi.org/10.1016/j.pnucene.2013.11.010

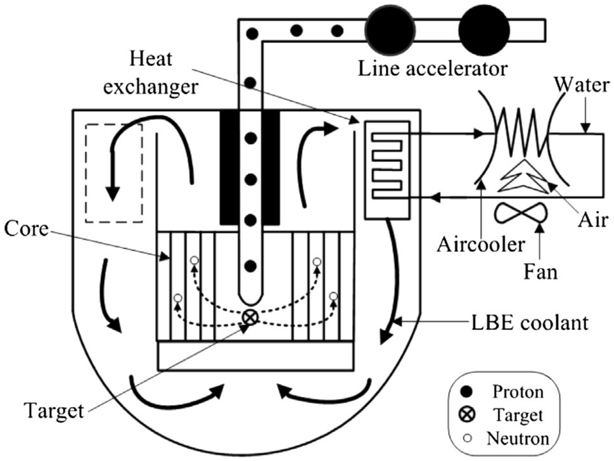

Fig. 1. Schematic of the CLEAR-IB system.

the simulation results followed by the summary and conclusions in Section 5.

2. Plant description

As shown in Fig. 1, in the core, protons from a linear accelerator are introduced into the target and then hit the lead target. As the result of a spallation process, neutrons will be supplied to the reactor core. The heat produced in the core will be carried out by the LBE coolant. The CLEAR-IB system consists of four modules and each module comprise of a portion of a single core/primary coolant pool and separate dedicated secondary circuits including heat exchangers, air coolers, fans, etc. The primary system is pool-type, similar to that of other metal-cooled reactors the core and all the primary LBE coolant of which are housed within the reactor vessel. The primary coolant leaves the core at 400 °C, and then enters the riser channels at the periphery of inner vessel. Natural circulation of LBE is enhanced by buoyancy force that is caused by the density difference between hot and cold temperatures. The secondary loop coolant system is made up of four independent loops. Each loop consists of one air cooler, and one heat exchanger (HX) immersed into the LBE that flows down through the downcomer and enters the core at 300 °C. The secondary side coolant of HXs is water, the pressure is 2.32 MPa. The water is cooled by the air in air coolers. The main design data are summarized in Table 1.

Since the design process of the CLEAR plant is still going on, the present work just reveals the preliminary results. The future work will partly remodel the equipments of the plant such as HXs and air coolers.

3. Modeling methodology and mathematical formulation of the plant

3.1. Philosophy of modeling

A simplified low order dynamic model with clear physical meaning is well appreciated for the dynamic characteristics research and control system design. For this reason, the lumped parameter technique is used to develop the dynamic model based upon the fundamental conservation of mass, energy and momentum, combined by algebraic equations such as empirical relationship equations, heat transfer equations and pressure drop equations (Fazekas et al., 2007; Roffel and Betlem, 2006).

Table 1
Main design data of CLEA-IB.

Parameters	Unit	Value
Core power	MW	10
Primary coolant	–	LBE
Core inlet temperature	°C	300
Core outlet temperature	°C	400
Coolant mass flow rate in the core	kg/s	690
Coolant velocity in the core	m/s	0.16
Effective core sub-criticality	–	0.98
Fission fuel	–	UO_2 (19.75%)
Driving force on the LBE	–	Buoyancy force
Secondary coolant	–	Water
HXs secondary side coolant pressure	MPa	2.32
HXs secondary side coolant inlet temperature	°C	215
HXs secondary side coolant outlet void fraction	°C	0.7531
HXs secondary side coolant mass flow rate	kg/s	103
Heat sink	–	Air coolers
Air coolers secondary side coolant inlet temperature	°C	30
Air coolers secondary side coolant outlet temperature	°C	190
Driving force on the air	–	Fan blowers
Fan blowing rate	m^3/s	67.9
Cladding	–	316Ti
Structure	–	316L

The laws of conservation (Roffel and Betlem, 2006) of mass, energy and momentum are applicable to each defined system and lumped to the form as follows:

$$\frac{\partial \rho}{\partial t} = \mp\frac{\partial G}{\partial z} \tag{1}$$

$$\frac{\partial(\rho H)}{\partial t} = \mp\frac{\partial(GH)}{\partial z} \pm \frac{Q}{A} + \frac{\partial P}{\partial t} \tag{2}$$

$$\mp\frac{\partial G}{\partial t} = -\frac{\partial\left(G^2/\rho\right)}{\partial z} - \frac{\partial P}{\partial z} - \frac{1}{2}\frac{f}{\rho}\frac{G|G|}{D_e} - \rho g \tag{3}$$

where ρ is density and G is mass flow rate, H and Q denote the specific enthalpy and heat flux, P and g denote Pressure and Gravitational acceleration, f and D_e denote resistance coefficient and equivalent diameter.

3.2. Overall modeling assumptions

The following major assumptions are made to simplify the formulation of the model:

1. The whole plant is divided into many sections, and each section is lumped to have uniform properties such as pressure, mass flow rate and temperature;
2. The LBE is incompressible and its density is treated as constant except for the buoyancy terms;
3. The axial conductive heat transfer is negligible along each loop;
4. The upper channel, upper plenum, downcomer and down plenum of the plant are treated as heat insulation only considering friction pressure drop in these parts.
5. The four modules have identical design features and dynamic characteristic.
6. The four modules are treated as one equivalence module.