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Flashing-driven natural circulation characteristics analysis of a natural circulation integrated pressurized water reactor

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ABSTRACT

In this paper, the simulation model of a flashing-driven natural circulation integrated pressurized water reactor is established based on RELAP5/Mod3.4 code. The distinctive characteristics involved in the reactor, such as flashing-driven natural circulation and self-pressurization, are revealed. Based on the thermal-hydraulic characteristics of the reactor, the operation scheme that maintains both core outlet temperature and steam pressure constant is determined. A temperature-pressure joint control strategy is preliminarily determined. Based on the established reactor model, the thermal-hydraulic characteristics of the IP100 reactor at different thermal load are analyzed. The results indicate that, at lower load, the onset of flashing will move downwards and the coolant flow rate decreases, while the core inlet temperature is higher. However, the mutual coupling effect leads to the thermal-hydraulic parameters of the reactor non-linearly varies with the needed load. In the secondary loop, the steam temperature is higher at lower load. Furthermore, the effect of main system parameters is analyzed and the criteria for reactor operation parameters are discussed. The obtained research results are significant for deeper understanding the thermal-hydraulic performance of the flashing-driven NC-IPWR.

1. Introduction

In recent years, with the continuous development of nuclear power technology and the increasing demand for electricity, integrated PWR (IPWR) has attracted more and more attentions. Compared with traditional PWRs, IPWR have obvious advantages in the aspects of flexibility, economy and safety performance. The modular design and bulk components fabrication offer the IPWR the convenience in staggered construction schedule, quick deployment and equipment transportation, which decreases the total capital costs of the plant. More importantly, the IPWR is able by design to eliminate some of the accidents, decrease the probability of occurrence for the vast majority of the remaining accidents, and mitigate the consequences (Carelli and Ingersoll, 2014). Since 1968, the first commercial IPWR was used in the NS Otto Hahn merchant ship, the IPWRs have been and continue to be a global R&D focus(Freire and Andrade, 2015). So far, more than 20 IPWR designs have been developed by research organizations worldwide(Rowinski et al., 2015). In viewing the development history of the IPWR, improving the inherent safety level and utilizing the passive techniques are significant developing directions of the IPWR(Agency, 2013). As an effective measure to improve the reactor's inherent safety performance, natural circulation has been extensively used in the passive safety systems of the current IPWR designs. Furthermore, in some advanced IPWR, natural circulation is utilized as the coolant circulating type. In future generation of nuclear plants, natural circulation will be used for ensuring the normal operating conditions in a wider spectrum than foreseen for current integrated reactor(Agency, 2012; Kuznetsov, 2004). Currently, the number of natural circulation IPWR (NC-IPWR) designs is still limited. The representative ones are MASLWR (Modro et al., 2003), CAREM (Fukami and Santecchia, 2000), NuScale (Ingersoll et al., 2014), ABV-6M (Agency, 1997). In these reactor designs, a variety of improvements are applied in order to promote the reactor's natural circulation capability, among which increasing the height difference between the hot leg and cold leg of the primary circuit, and reducing the flow resistance by optimizing the coolant flow channel are most general. Besides these common measures, two-phase flow characteristics are also used to promote the natural circulation performance of the reactor. In CAREM-25 reactor, the flashing-driven two phase flow natural circulation is used as the coolant circulating type and the pressurization method (Marcel et al., 2013). In a natural circulation loop, flashing which occurs in the chimney can effectively increase the density difference between hot leg and cold leg of the loop, thereby increasing the natural circulation driving pressure head. In addition, the flashing-driven passive moderator circulation system (PMCS) is considered using as the removal of moderator heat under both normal and accident conditions in an advanced CANDU reactor

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concept (Dimmick et al., 2002; Yang, 2014).

In order to clarify the flashing characteristics in a natural circulation loop, a series of experimental researches have been carried out (Guo et al., 2016; Manera et al., 2006; Ozar et al., 2013). Large-scale thermal-hydraulic system analysis program, such as RELAP5(Shi et al., 2018) and HUARPE(Zanocco et al., 2004), are also used to analyze the flashing characteristics involved in the natural circulation system. In addition, many numerical models are developed to predict the flashing and flashing instability of a natural circulation loop (Bragt and Hagen, 1998; Guo et al., 2015; Manera et al., 2005). The complex coupling mechanism makes the characteristics of the flash-driven two-phase natural circulation loop complicated. Due to the adoption of flashing technique, the operation scheme and the thermal-hydraulic characteristics of the flashing-driven NC-IPWR are significantly different from those of other natural circulation pressurized water reactors. The researches on relevant phenomenon and characteristics involved in the flashing-driven NC-IPWRs are still deficient.

In this paper, the steady-state thermal-hydraulic performance of the natural circulation integrated pressurized water reactor are expounded specifically. The REALP5/Mod 3.4 code is used to establish the model of reactor coolant system (RCS) of the IPWR. The mechanisms of two-phase natural circulation with flashing and self-pressurization are revealed according to the simulation model. The steady-state operation characteristics of the reactor at different load conditions are investigated. In addition, the effect of some system parameters is analyzed.

2. Description of research model

2.1. A brief description of reactor

Fig. 1 shows the basic structure of the IP100 reactor. IP100 reactor is a natural circulation integrated pressurized water reactor with a thermal power of 110MWt, which adopts the full integrated configuration, with all the major RCS components including reactor core, steam generators, pressurization space and INV-CRDM being contained in the reactor pressure vessel (RPV). Thus, all large coolant pipes are eliminated, and the large-break LOCA accident is prevented entirely. In addition, the full integrated layout design requires a large RPV, which enlarges the amount of coolant accommodated in the RPV and increases the overall heat capacity of the system. The Major parameters of the IP100 reactor are listed in Table 1.

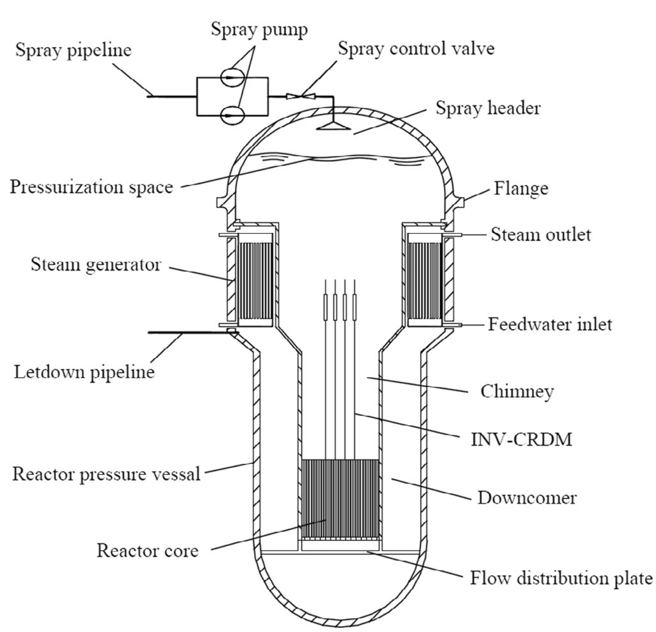

Fig. 1. Schematic diagram of the IP100 reactor.

Table 1
Main parameters of the IP100 reactor.

Parameter	Value
RCS	
Primary loop pressure	15.0 MPa
Thermal power	110 MWt
circulating type	Natural circulation
pressurization type	Self-pressurization
Height of the fuel assembly	1.5 m
Reactor core heat transfer area	468.7 m^2
Reactor core outlet temperature	615 K
Fuel material	Platy UO_2
Spray water temperature	600 K
OTSG	
Steam pressure	3.0 MPa
Feedwater temperature	373.15 K
Feedwater flow rate	43.8 kg/s
Steam temperature	538.15 K
Length of tube	1.5 mm
Tube material	Ti-alloy
Heat transfer area	150 m^2

The reactor core is placed in the lower elevation of the RPV. The assembly utilizes the plate type fuel elements, and forms a hexagonal shape. The IP100 reactor employs in-vessel control rod drive mechanism (INV-CRDM) to eliminate the possibility of a reactivity insertion accident caused by control rod withdrawal.

Casing once-through steam generators (OTSGs) are located at the upper part of the RPV surrounding the chimney. The heat transfer tube of the casing OTSG adopts narrow annular gap structure and double-faced heat transfer, which has large heat transfer area and higher volumetric heat exchange rate. In primary side, the coolant flows in the inner tube and the outside of the outer tube. In the secondary side, the feedwater flows in the annuli channels between the inner tube and outer tube, and then turns to superheated steam at 3.0 MPa. A large integrated pressurization space is located at the top of the RPV. The chimney and the pressurization space are connected directly, ensuring the vapor generated in the chimney flowing upward into the pressurization space without any obstruction. A spray system, which shares pipelines with the coolant purification system, is installed at the top of the pressurization space.

2.2. Thermal-hydraulic model

The thermal-hydraulic model of the IP100 reactor is established by RELAP5/Mod 3.4 code. RELAP5 code is a best-estimate system code for the simulation of LWR systems and as a basis for nuclear plant analyzers (Sloan et al., 1992). The one-dimensional two-fluid field equations work as the basis for RELAP5 code, which are solved by semi-implicit finite-difference technique. Constitutive relations and correlations are used to close the field equations, among which includes the interfacial heat and mass transfer relations between gas and liquid, making the RELAP5 code have the ability to reveal the subcooled boiling and flashing phenomenon(Co, 1995). By comparing the calculation results of RELAP5 and experimental data, many studies have proved that RELAP5 code can accurately simulate the flashing phenomenon in a natural circulation loop (Fullmer et al., 2016; Kozmenkov et al., 2012; Mangal et al., 2012).

The nodalization of the IP100 reactor is shown in Fig. 2. Reactor core is divided into 3 channels: the hot channel (016P), the average channel (018P) and the bypass channel (020P). All three channels are divided into 10 axial nodes. Point reactor neutron kinetics model is adopted to provide the reactor power needed during the simulation process. As complex flashing and condensation phenomenon occurs in the chimney, the chimney pipe (024P) is divided into 50 control volumes to demonstrate the two-phase heat and mass transfer process.

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