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Analysis of flow distribution in plate-type core affected by uneven inlet temperature distribution

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ABSTRACT

The flow and power distribution characteristics of plate-type fuel reactor core have been investigated in the present study. A reactor core thermal-hydraulic and neutronics coupled model was established using RELAP5-3D codes. The coupled modeling method was used to establish the thermo-hydraulic model, and the phenomenon of two-phase flow instability in a parallel two-channel system was used to verify the reliability of the method. Besides, the influence on power and flow distributions of uneven core inlet temperature was also studied by the application of coupled three-dimensional neutron-kinetics and thermal-hydraulics. The results show that, the coupled modeling method is reliable and can be used to establish the thermo-hydraulic model of a reactor core. By this method, both the effects of heating power and inlet temperature on flow distribution have been studied. The flow and power distributions of reactor core are inseparable and have a great effect on each other under the strong coupling of thermal-hydraulic and neutronics, but the non-uniformity of power distribution is greater than flow distribution. When reactor core inlet temperature distribution is uneven, reactor power peaking factor shifts to the low inlet temperature region, and flow peaking factor shifts to the high inlet temperature region. The effect of uneven core inlet temperature on flow distribution has a far greater impact than reactor power.

1. Introduction

In recent years, plate-type fuel assemblies have been widely used in the design of advanced reactors (IAEA-TECDOC-233, 1980; Liu et al., 2006). The reactor core is composed of a number of parallel thin rectangular channels which have very good flow and heat transfer characteristics. And the highest fuel central temperature of fuel plate is relatively low. All of the above are beneficial to improve the reactor safety margin. However, there is no flow mixing between parallel coolant channels, the inappropriate flow distribution in reactor core may lead to local dryout and fuel integrity damage at particular channels. Therefore, it is necessary to study the flow distribution characteristics of plate-type reactor core.

The flow distribution of reactor core is one of the most important concerns for the design of a nuclear reactor, many associated research works have been carried out. Tian et al. (2005) analyzed the flow distribution of China Advanced Research Reactor (CARR), the research showed that the structure size played the most important role in the flow distribution and the influence by core power could be neglected. Chen et al. (2014) analyzed the core flow distribution of a 10 MW natural circulation lead-alloy cooled fast reactor, the results illustrated that the increase rate of mass flow rate is smaller than the increase rate of power. Bae et al. (2013) investigated the flow distribution at the core inlet region of the System-integrated Modular Advanced Reactor (SMART) using numerical methods, the results showed that lower core support plate effectively distributed the flow at the core inlet. Otherwise, several researches have been performed on partial and total obstruction of the cooling channel (Martina et al., 2005; Amgad and Salah, 2011; Davari et al., 2015).

Coolant channels in the standard fuel assembly are separated from each other. In some special conditions, the heating power and inlet mass flow rate change may cause two-phase flow instability. The most common dynamic flow instability type in parallel channel system is called the density wave oscillations (DWOs), the mass flow rate of each channel undergoes out-phase flow oscillation (Guo et al., 2010; Xia et al., 2012; Qian et al., 2014). Ledinegg instability is one of the most important static instability in narrow channel system, the transient process represent as sudden large amplitude excursion to a new stable operating condition (Yeoh et al., 2004; Tewfik and Anis, 2006; Kuo and Peles, 2009). The flow instability can lead to flow redistribution between parallel chan-

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Table 1
Main design parameters of IP200.

System parameters	Designing values
Initial core power (100%)	220.0 MW
Reactor core inlet temperature	562.15 K
Reactor core outlet temperature	594.15 K
Pressurizer pressure	15.5 MPa
Primary coolant mass flow rates	1200.0 kg/s
Initial feed water mass flow rate	81.6 kg/s
Main feedwater temperature	373.15 K
Main steam pressure	3.0 MPa
Superheat of steam (100%FP)	40.0 K
Main pump number	4
OTSG number	12
Core material	
Fuel type	Plate type
Fuel used	UO_2
Clad material	Zircaloy
Maximum fuel enrichment	4.5%
Core parameters	
No. of fuel assemblies	121
No. of fuel plates in one assembly	$12 \times 4 = 48$
Total fuel plate thickness	1.8 mm
Fuel meat thickness	1.2 mm
Cladding thickness	0.3 mm
Fuel width	50.0 mm
Water channel thickness	2.0 mm
Total fuel plate height	1200.0 mm

nels, and the change of mass flow rate will seriously affect the safe operation of the reactor.

IP200 reactor core (Xu et al., 2010) is composed by plate-type fuel elements. The flow distribution and power distribution of reactor core are inseparable and have a great effect on each other under the strong coupling of thermal-hydraulic and neutronics. Especially in OTSG (Once-through Steam Generator) asymmetrical operation conditions, uneven core inlet temperature affects not only the flow distribution but also the power distribution of reactor core. The purpose of this paper is to study the flow distribution and power distribution characteristics of plate-type fuel reactor core at uniform inlet temperature conditions.

2. Research model

2.1. Brief introduction of the reactor

The reactor core, pressurizer, four main pumps and twelve once-through steam generators are all inside of reactor pressure vessel. Major design parameters of IP200 reactor are shown in Table 1. The reactor power for normal operating conditions is 220.0 MW, and total core mass flow rate is 1200.0 kg/s. Operation at full power, the core inlet temperature and outlet temperature are 562.15 K and 592.15 K respectively. Feed water is heated to superheated steam by primary coolant. The feed water inlet temperature is 373.15 K, and the steam superheat degree is 40.0 K at 100% FP conditions. Under the ideal steady-state operation mode, nuclear power plant can retain both the primary coolant average temperature and the secondary side steam pressure when its steady power changes.

The reactor utilizes the metal matrix dispersion plate type fuel. The fuel element consists of the metal cladding (Zr-4) and the dispersion plate type fuel meat (UO_2 dispersed in the Zr-2 matrix). The detailed specifications of the core are shown in Table 1. The reactor core includes 121 fuel assemblies, each fuel assembly has four unit assemblies. The arrangement of the unit assembly is depicted in Fig. 1. The standard unit assembly contains 12 diffuse plate-type fuel elements. And the narrow gap between fuel plates

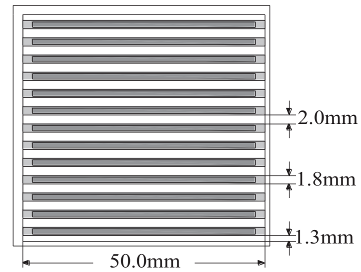
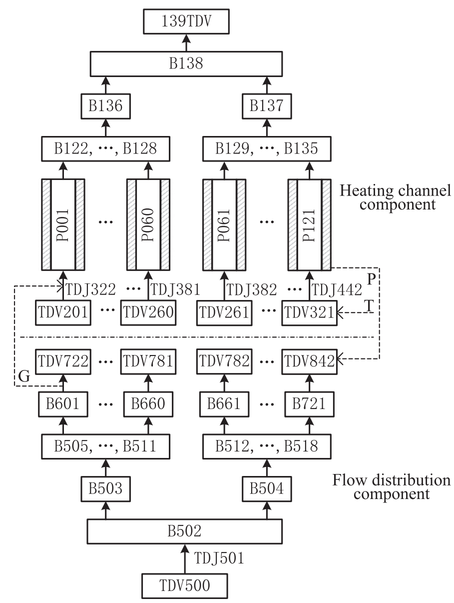
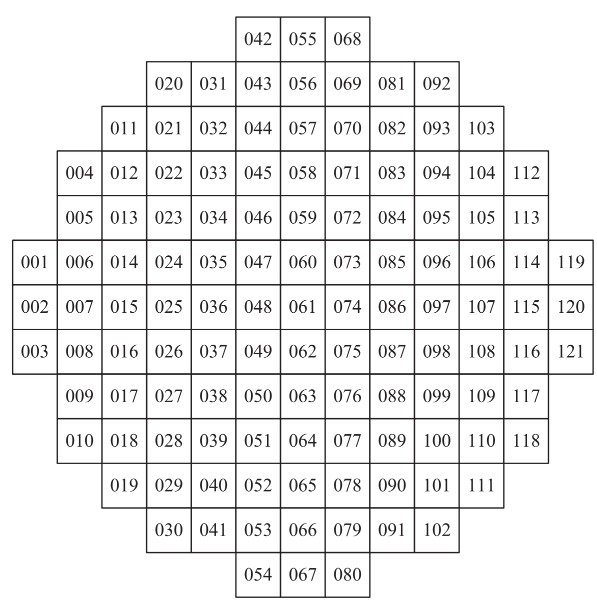


Fig. 1. The arrangement of fuel plate in a unit fuel assembly.



a. Axial node division.



b. Radial distribution of the parallel channels.

Fig. 2. The thermo-hydraulic model of reactor core.

constitutes the flow channels of primary coolant. Water flows through these narrow flow channels to remove heat from fuel plates.