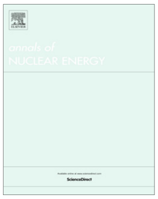
Annals of Nuclear Energy 72 (2014) 76–83

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Study of core flow distribution for small modular natural circulation lead or lead-alloy cooled fast reactors

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ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 7 April 2014
Accepted 26 April 2014
Available online 23 May 2014

Keywords:
Core flow distribution
Natural circulation
Small modular
LFR

ABSTRACT

Small modular natural circulation lead or lead-alloy cooled fast reactor (LFR) is a potential candidate for LFR development. It has many attractive advantages such as reduced capital costs and inherent safety. The core flow distribution calculation is an important issue for nuclear reactor design, which will provide important input parameters to thermal-hydraulic analysis and safety analysis. The core flow distribution calculation of a natural circulation LFR is different from that of a forced circulation reactor. In a forced circulation reactor, the core flow distribution can be controlled and adjusted by the pump power and the flow distributor, while in a natural circulation reactor, the core flow distribution is automatically adjusted according to the relationship between the local power and the local resistance feature. In this paper, a non-uniform heated parallel channel flow distribution calculation code was developed and the comparison study between the channel method and the CFD method was carried out to assess the exactness of the developed code. The core flow distribution analysis and optimization design for a 10MW natural circulation LFR was conducted using the developed code. A core flow distribution optimization design scheme for a 10MW natural circulation LFR was proposed according to the optimization analysis results.

1. Introduction

Lead or lead-alloy cooled fast reactor (LFR) has many good properties, such as chemical inertness with air and water (unlike sodium), high boiling point, high atomic number and low vapor pressure (IAEA, 2012). It has been selected as one of the six types of advanced reactors in the Generation IV International Forum (GIF) Smith et al., 2009. Small modular natural circulation LFR is a potential candidate for LFR development, owing to its attractive advantages like reduced capital costs and inherent safety (IAEA, 2007). Several small modular natural circulation LFR concepts have been developed in the world. In Europe, a natural circulation LFR had been developed to serve as the sub-critical reactor of an Accelerator Driven System (ADS) named Energy Amplifier (EA) (Rubbia et al., 1995). In the United States, a natural circulation LFR had been developed to serve as an actinide burning and low cost electricity producing reactor (MacDonald and Todreas, 2000; Buongiorno et al., 2001; MacDonald and Buongiorno, 2002), and several small modular natural circulation LFR concepts including SSTAR and SUPERSTAR, have been developed for international nuclear energy development (Sienicki, 2006; Smith, 2008; Sienicki et al., 2011). In China, a small natural circulation LFR has been developed for the ADS development under the supported of the Chinese Academy of Sciences (CAS) Strategic Priority Research Program named “Advanced Nuclear Fission Energy-ADS Transmutation System” (Zhan et al., 2012; Chen et al., 2012).

The core flow distribution calculation is an important issue for nuclear reactor design, which will provide important input parameters to thermal-hydraulic analysis and safety analysis (Wang et al., 1999). Many researchers investigated the core flow distribution of different type of reactors. Li et al. (2002) conducted experiments and numerical simulations to optimize flow distribution in an advance pressurized water reactor. Liu et al. (2003) and Tian et al. (2005) analyzed the core flow distribution of a pool-type water cooled research reactor named CARR. Li et al. (2011) analyzed core flow distribution of a supercritical water cooled reactor. Bae et al. (2013) analyzed the flow distribution at the core inlet of a system-integrated modular advanced reactor named SMART.

The core flow distribution calculation of a natural circulation LFR is different from that of a forced circulation reactor. In a forced circulation reactor, the core flow distribution can be controlled and adjusted by the pump power and the flow distributor, while in a natural circulation reactor, the core flow distribution is automatically adjusted according to the relationship between the local

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http://dx.doi.org/10.1016/j.anucene.2014.04.032
0306-4549/

Nomenclature

A_n	flow area of channel n (m^2)
A_{core}	flow area of core region (m^2)
A_{HE}	flow area of heat exchanger (m^2)
$c_{p,in,n}$	thermal capacities of coolant at the inlet of channel n (J/kg K)
$c_{p,out,n}$	thermal capacities of coolant at the outlet of channel n (J/kg K)
$c_{p,Pb}$	thermal capacities of lead (J/kg K)
$c_{p,LBE}$	thermal capacities of lead–bismuth eutectic (J/kg K)
$D_{e,n}$	hydraulic diameter of channel n (m)
$D_{e,core}$	hydraulic diameter of core region (m)
$D_{e,HE}$	hydraulic diameter of heat exchanger (m)
dz	axial length (m)
f_n	friction coefficient of channel n
f_{core}	friction coefficient of core region
f_{HE}	friction coefficient of heat exchanger
$f_{Blasius}$	Blasius friction coefficient
$f_{Novendstern}$	Novendstern friction coefficient
g	gravity acceleration (m/s^2)
H/D	dimensionless height-to-diameter of wire
K	form coefficient
K_n	form coefficient of channel n
K_{core}	form coefficient of core region
K_{HE}	form coefficient of heat exchanger
K_{inlet}	form coefficient of assembly inlet
K_{outlet}	form coefficient of assembly outlet
L_n	length of channel n (m)
L_{core}	length of core region (m)
L_{HE}	length of heat exchanger (m)
P/D	dimensionless pitch-to-diameter
$p_{ch,in,n}$	inlet pressure in channel n
$p_{ch,out,n}$	outlet pressure in channel n
$\Delta p_{ch,n}$	pressure drops of channel n
Δp_{loop}	sum of all pressure drops in the whole system
Δp_{core}	pressure drop of core
ΔP_{form}	form pressure drop
$\Delta p_{downcomer}$	pressure drop of downcomer region (Pa)
Δp_{HE}	pressure drop of heat exchanger (Pa)
Δp_{riser}	pressure drop of riser region (Pa)
Q_n	thermal power of channel n (W)
$T_{in,n}$	temperature at the inlet of channel n (°C)
$T_{out,n}$	temperature at the outlet of channel n (°C)
ΔT_n	temperature different of channel n (°C)
v	coolant velocity (m/s)
v_n	coolant velocity of channel n (m/s)
W_n	mass flow rate of channel n (kg/s)
$W_{in,n}$	mass flow rate at inlet of channel n (kg/s)
$W_{out,n}$	mass flow rate at outlet of channel n (kg/s)
W_t	total mass flow rate of all channel (kg/s)
W_{core}	mass flow rate of core region (kg/s)
W_{HE}	mass flow rate of heat exchanger (kg/s)

Greek symbols

β	coolant expansion coefficient (k^{-1})
ρ	coolant density (kg/m^3)
ρ_0	coolant density at reference temperature (kg/m^3)
ρ_n	coolant density of channel n (kg/m^3)
ρ_{core}	coolant density of core region (kg/m^3)
ρ_{riser}	coolant density of riser region (kg/m^3)
$\rho_{downcomer}$	coolant density of downcomer region (kg/m^3)
ρ_{HE}	coolant density of heat exchanger region (kg/m^3)
ρ_{Pb}	density of lead (kg/m^3)
ρ_{LBE}	density of lead–bismuth eutectic (kg/m^3)

power and the local resistance feature. It is a challenging work to make an accurate calculation of the core flow distribution of a small modular natural circulation LFR. As far as we know, there is no open literature focused on the core flow distribution of a small modular natural circulation LFR.

In this paper, a non-uniform heated parallel channel flow distribution calculation code was developed and the comparison study between the channel method and the CFD method was carried out to assess the exactness of the developed code. The core flow distribution analysis and optimization design for a 10MW natural circulation LFR was conducted using the developed code.

2. Calculation code development

2.1. Parallel channel flow distribution model

The parallel channel flow distribution model used in the developed code was developed by Chato (1963). The model can be described as below.

Considering N uniform, vertical, interconnected, parallel channels as shown in Fig. 1, the pressure drop from the inlet (bottom) to the outlet (top) in any channel can be written as:

$$\begin{aligned}\Delta p_{ch,n} &= p_{ch,in,n} - p_{ch,out,n}\\ &= \int_0^{L_n} \rho_n g dz + f_n \frac{L_n W_n^2}{2\rho_n A_n^2 D_{e,n}} + K_n \frac{W_n^2}{2\rho_n A_n^2}, \quad n = 1,2,3,\ldots N \end{aligned} \tag{1}$$

With the assumption that the inlet pressure and outlet pressure of each channel are equal, the pressure equilibrium among all channels can be expressed as:

$$\Delta p_{ch,1} = \Delta p_{ch,n} \quad n = 1,2,3,\ldots N \tag{2}$$

The mass conservation equation is:

$$W_t = \sum_{n=1}^{N} W_n = \sum_{n=1}^{N} \rho_n v_n A_n \quad n = 1,2,3,\ldots N \tag{3}$$

Therefore, the problem of natural circulation flow distribution of a parallel channel system is to solve the following equation set:

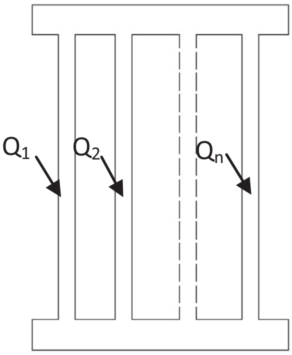

Fig. 1. Uniform, vertical, interconnected, parallel channels model.