Annals of Nuclear Energy 50 (2012) 199–205

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

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

The development of natural circulation operation support program for ship nuclear power machinery

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ARTICLE INFO

Article history:
Received 26 February 2012
Received in revised form 1 August 2012
Accepted 7 August 2012
Available online 21 September 2012

Keywords:
Ship nuclear power machinery
Operation support program
Natural circulation
Ocean condition

ABSTRACT

The existing simulation program of ship nuclear power machinery (SNPM) cannot adequately deal with the natural circulation (NC) operation and the effects of various ocean conditions and ship motion. Aiming at the problem, the natural circulation operation support computer program for SNPM is developed, in which the momentum conservation equation of the primary loop, some heat transfer and flow resistance models and equations are modified for the various ocean conditions and ship motion. The additional pressure loss model and effective height model for the control volume in the gyration movement, simple harmonic rolling and pitching movements are also discussed in the paper. Furthermore, the transient response to load change under NC conditions is analyzed by the developed program. The results are compared with those predicted by the modified RELAP5/mod3.2 code. It is shown that the natural circulation operation support program (NCOSP) is simple in the input preparation, runs fast and has a satisfactory precision, and is therefore very suitable for the operating field support of SNPM under the conditions of NC.

1. Introduction

The barge-mounted nuclear power plant for desalination has shorter construction period, simplified anti-seismic design measure and the ability to move to almost any coastal place when compared with land-based nuclear power plant (Panov et al., 1998). The nuclear power machinery can operate continuously for a very long time having no use for air which is of significance to ship especially the submarine (Ishida and Yoritsune, 2002). All these nuclear power facilities in the ship are inevitably influenced by the ocean condition (Zhong et al., 2009) which will change the force on the fluid and induce the flow fluctuation and therefore change the characteristics of flow and heat transfer (Pendyala et al., 2008a,b). It is shown that the effect of the ocean condition on the forced circulation (FC) is insignificant, but the effect on the natural circulation (NC) is significant. Therefore a series of experimental and theoretical researches on the NC characteristic under the ocean condition are carried out by many investigators. Gao (1999) established the basic theoretical model of ocean condition and analyzed the effect of rolling and pitching on NC. Murata et al. (2002) carried out the experiment of single phase NC flow and analyzed the effect of rolling on thermal–hydraulics characteristic of NC. Based on the modified RETRAN-02 code Ishida and Yoritsune (2002) studied the effect of heeling and heaving on the operation characteristic of a small integral reactor for deep sea research.

The ship nuclear power machinery (SNPM) is characterized by the high maneuverability, fast and sharp power change (Zhang et al., 2009; Li et al., 2010a,b; Wang et al., 2011; Chen et al., 2012b). In order to quickly and accurately forecast the parameters response during the transient process at the operating field, an operation support program (OSP) is established with Simulink by Chen et al. (2012a). The OSP has the properties of simple input preparation, fast and accurate simulation, but cannot be used to the NC operation condition and the ocean and ship motion conditions. Therefore the main purpose of this paper is to develop a fast simulation program on the basis of aforementioned OSP to support the NC operation of SNPM.

2. Physical and mathematical model

The SNPM considered in this paper is equipped a pressurize water reactor (PWR) with double loops. The detailed parameters and arrangement can be found in Yan and Yu (2009). The control volume division of the reactor and primary loop is shown in Fig. 1. All of the heat is assumed to be yielded in the fuel rod and the moveable boundary control volume (Gal and Saphier, 1991) is adopted in the model of steam generator (SG), therefore the division in Fig. 1 has some difference with those in Yan and Yu (2009). The point-reactor kinetics equations with six-group delayed neutrons (Li et al., 2009) are adopted, and the reactivity feedback by the core coolant and fuel temperature (Li et al., 2007, 2010a,b)

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http://dx.doi.org/10.1016/j.anucene.2012.08.005

Nomenclature

Symbols

a	acceleration (m/s^2)
D	diameter (m)
g	acceleration of gravity (m/s^2)
$\vec{i}$	unit vector of x direction
$\vec{k}$	unit vector of z direction
K	local pressure loss coefficient
p	pressure of primary loop (MPa) pressure loss (Pa)
r	radius shown in Fig. 5 (m)
t	time (s)
v	specific volume (m^3/kg)
x, y, z	coordinate
A	section area (m^2)
f	frictional loss coefficient
H	head of main pump (m)
$\vec{j}$	unit vector of y direction
k_{c1}, k_{c2}	coefficient of ratio
L	length of control volume (m)
P	power (kW)
R	radius of gyration (m)
T	period (s)
W	mass flux (kg/s)

Greek letters

ω	angle speed (rad/s)
θ	angle (rad)
β	angle acceleration (rad/s^2)

Subscripts

a	additional
i	ith
n	normal
t	tangent
z	vertical direction, left loop
e	equivalent
in	inlet
o	outlet
y	right loop

and the reactivity inserted respectively by one group of auto-controlled and manual-controlled rods are considered.

The fluid in the primary loop is assumed to be in single phase except for in the pressurizer. The main difference in the physical model between this paper and Chen et al. (2012a) is the momentum conservation equation. In the present work the additional pressure losses caused by various ocean conditions and ship motion are involved in the momentum equation, and the coefficients of frictional and local resistance are modified according to the model by Yan and Yu (2009). The momentum conservation equation of one dimension flow in the control volume along the $\vec{L}$ direction can be written as follows:

$$\frac{L}{A}\frac{dW}{dt}+\frac{\partial}{\partial \vec{L}}\left(\frac{L v W^2}{A^2}\right) = -L\frac{\partial p}{\partial L} - f\frac{L v W^2}{2D_e A^2} - K\frac{v W^2}{2A^2} - \frac{L_z g}{v}\frac{d\vec{z}}{d\vec{L}} \qquad (1)$$

where W is the coolant mass flux, kg/s; L and L_z are the length and effective height of the control volume, respectively, m; D_e is the equivalent diameter, m; A is the area of cross section, m^2; v is the average specific volume of coolant, m^3/kg; p is the pressure, Pa; g is the acceleration of gravity, m/s^2; f is the frictional pressure loss coefficient; K is the local pressure loss coefficient; $\vec{z}$ is the vertical up direction; $\vec{L}$ is the direction of coolant flow in the control volume. The side flow and leakage flow in reactor core are considered as shown in Fig. 1. For the simplification the ratio of main mass flux

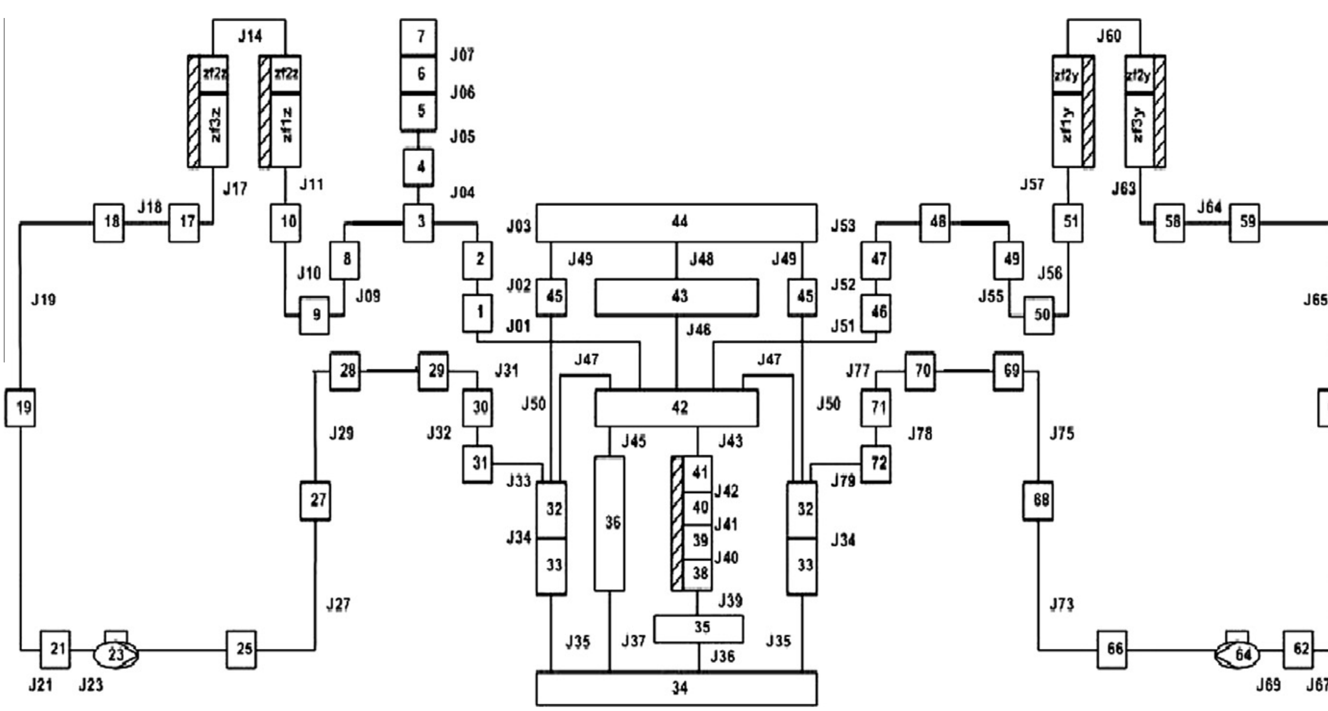

Fig. 1. Control volume division of reactor and primary loop for SNPM.