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The development and application of a sub-channel code in ocean environment

Pan Wu, Jianqiang Shan *, Xiong Xiang, Bo Zhang, Junli Gou, Bin Zhang

School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

An upgraded version of ATHAS sub-channel code ATHAS/OE is developed for the investigation of the thermal hydraulic behavior of nuclear reactor core in ocean environment with consideration of heaving and rolling motion effect. The code is verified by another modified sub-channel code based on COBRA-IV and used to analyze the thermal hydraulic characteristics of a typical SMR under heaving and rolling motion condition. The calculation results show that the heaving and rolling motion affect the thermal hydraulic behavior of a reactor significantly.

1. Introduction

In recent years, there is a growing interest in a floating nuclear power plant which adopts a small module reactor (SMR) as its energy source. Such plants can be used in the offshore region to supply power to the remote areas (Panov et al., 1998). Reactors mounted on such plants will be operated in ocean environment. From a fluid mechanics point of view, the main difference between nuclear reactor built on land and in ocean environment is the influence of sea wave oscillations in the latter case (Zhong et al., 2009). The thermal–hydraulics behavior of a nuclear reactor in ocean environment is influenced by complicated motions which are usually decomposed into several one-dimension ones such as pitching, heaving and rolling. These motions change the effective forces on the fluid and induce flow fluctuations, which will result in a change in momentum, heat and mass transfer characteristics in the nuclear reactor system (Pendyala et al., 2008). The thermo-hydraulic analyses of nuclear reactors in ocean environment are crucial in its evaluation process. So researches on reactors in ocean motion are carried out widely in the world.

There are many investigations on flow and heat transfer mechanics in ocean environment in the open literature. Ishida et al. (1995) investigated the thermal hydraulics behavior of a marine reactor in ship motions. Their results indicates that the loop mass flow rate varies with rolling motion. The core flow rate exhibits a variation with rolling frequencies and a correlation is obtained based on the Reynolds number of rolling motion. A series of single-phase natural circulation experiments were carried out and the effect of rolling motion on the thermal hydraulics characteristics of reactor was obtained by Murata et al. (2002). The results show that the heat transfer in the core is enhanced by the rolling motion and the enhancement is thought to be caused by the internal flow due to the rolling motion. An experimental investigation on the effect of heaving on the flow in a single vertical tube was carried out and the pressure drop and heat transfer characteristics were obtained by Pendyala et al. (2008). Yan et al. (2010, 2012) and Yan and Yu (2011, 2012) achieved the pressure drop and heat transfer correlations under both laminar and turbulent flow in circular tubes and rectangular tubes in heaving and rolling motion theoretically, which were quite different from conventional form. Many experimental researches about two-phase flow in rolling motion were carried out by Cao (2006) and Zhang (2009). The flow patterns, pressure drop and heat transfer characteristics were obtained, and empirical or semi-empirical correlations were developed based on their experimental data.

Some nuclear reactor thermal–hydraulics system codes have been developed which can be used in ocean environment based on existing system codes in recent years. RETRAN/Grav was developed by Toshihisa and Ichio (1992) based on RETRAN-02/MOD2. It was verified through comparing with a two-phase natural circulation experimental data operated on the SG secondary side under heaving conditions. Yan and Yu (2011) developed an advanced thermal hydraulic code in rolling motion based on RELAP5/

* Corresponding author.
E-mail address: jqshan@mail.xjtu.edu.cn (J. Shan).

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Nomenclature

Symbol

a_k	heaving acceleration ($m \cdot s^{-2}$)
d	the centroid distance between two sub-channels (m)
F	axial flow rate ($kg \cdot s^{-1}$)
G	gravitational acceleration ($m \cdot s^{-2}$)
K	heaving constant
L	the distance from the fluid particle to rolling axis (m)
M	mass (kg)
n	rolling angle frequency
P	pressure (Pa)
q	heat transfer (W)
S	flow area (m^2)
t	time (s)
T	period (s)
x	x coordinate of the fluid particle (m)
y	y coordinate of the fluid particle (m)
z	z coordinate of the fluid particle (m)
w	the velocity of fluid particle in x direction ($m \cdot s^{-1}$)
W	lateral flow rate ($kg \cdot s^{-1}$)
v	the velocity of fluid particle in y direction ($m \cdot s^{-1}$)
V	lateral velocity ($m \cdot s^{-1}$)
u	the velocity of fluid particle in z direction ($m \cdot s^{-1}$)
U	axial velocity ($m \cdot s^{-1}$)
$\vec{a}$	acceleration vector
$\vec{F}$	additional force vector
$\vec{r}$	location vector of fluid particle
$\vec{u}_r$	relative velocity vector of fluid particle
$\vec{i}$	unit vector of x direction
$\vec{j}$	unit vector of y direction
$\vec{k}$	unit vector of z direction
θ	rolling angle
ω	angular velocity (s^{-1})
β	angular acceleration (s^{-2})
φ	gap angle
ρ	density ($kg \cdot m^{-3}$)
η	volume (m^3)
$\vec{\omega}$	vector of angular velocity
$\vec{\beta}$	vector of angular acceleration

Subscript

ii	sub-channel ii
jj	sub-channel jj
k	gap k
l	liquid phase
v	vapor phase
m	maximum

Acronyms

ATHAS	Advanced Thermal–Hydraulics Analysis Sub-channel
NUSOL	Nuclear Safety and Operation Laboratory

MOD3.3 code. The experimental data of a natural circulation system in rolling motion on a rolling apparatus were used to validate the theoretical models and the code. Tan et al. (2009) also developed RELAP5/MC and applied it to analyze the natural circulation characteristics of a simple two loop system in ocean environment and the results were reasonable.

As mentioned above, the thermo-hydraulic analysis of a nuclear reactor in ocean environment is the key of the floating nuclear power plant. The current experimental research study is restricted to single tube analysis, and the development of analysis tools used in ocean environment is restricted to system code. However, there is little information about sub-channel analysis of a nuclear reactor core in ocean environment in existing public literature, which is usually thought to be an effective method to obtain the detailed thermo-hydraulic characteristics of a nuclear reactor. The development of a sub-channel code which is applicable to reactors in ocean environment is quite necessary.

In this paper, a sub-channel code named ATHAS/OE, which is applicable to the ocean environment, is developed based on ATHAS (Shan et al., 2009, 2010). The code is obtained by incorporating an effect module of heaving and rolling motion into ATHAS. The developed sub-channel code is applied to thermo-hydraulics analysis of a typical SMR mounted on the floating nuclear power plant.

2. Theoretical models

ATHAS code is developed for analysis of flow and enthalpy distributions and cladding/fuel temperatures in the reactor core. The code is applicable for both transient and steady state calculations. ATHAS code adopts drift model to simulate the fluid flow in the reactor. Pressure–velocity correlation method is developed to get the numerical solution. A number of heat-transfer correlations, frictional resistance correlations, and mixing models have been implemented into the code as options for sensitivity analysis (Shan et al., 2009). In this paper, ATHAS code is upgraded to simulate the conditions in ocean environment by modifying the momentum-conservation equation and incorporating a new boundary condition and critical heat flux model.

2.1. Additional force

In ocean environment, the coolant flow in the reactor core is affected by the additional force. As shown in Fig. 1, a Cartesian coordinate system o-xyz is fixed on the barge (fixed on the

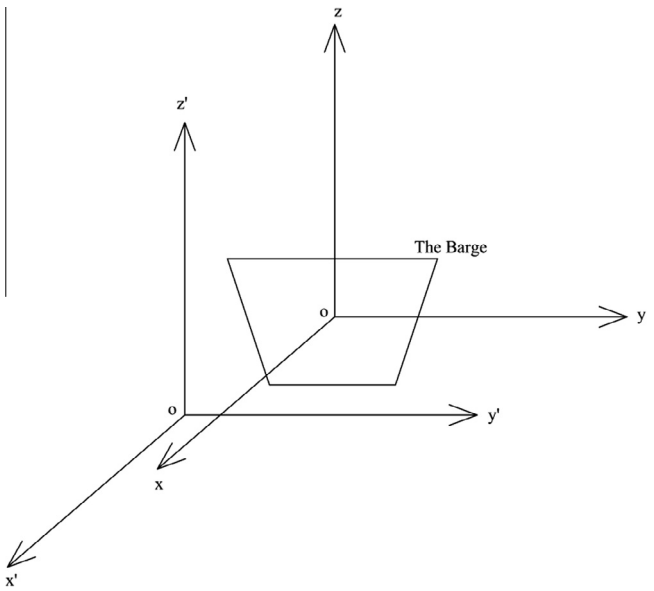

Fig. 1. Cartesian coordinate system fixed on the barge and the earth.