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The core instability analysis under ocean condition for offshore floating nuclear power plant with neutron coupling based on multi-point model

Miao Hu [a], Yun Guo [b,*]

[a] Department of Chemical and Materials Engineering, Hefei University, Hefei 230601, China
[b] School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230026, China

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ABSTRACT

For offshore floating nuclear power system the ocean conditions, such as rolling, must be considered for safe design. The neutron kinetics decides the power distribution and variation. Both of them will change the characteristics of the core instability. In this paper the ocean condition model and multi-point reactor model are added into the parallel channel system thermal-hydraulic model. A reactor core with 121 assemblies based on QinshanII nuclear power plant is selected as research object. The inherent instability of the system is studied firstly as the basis of comparison. Then the instability boundaries under motion condition and neutron feedback are obtained separately. The joint influence of motion and neutron feedback is studied. The results indicate that ocean condition has very limited effect for such system with so many parallel channels. Neutron feedback in different inlet subcooling regions have different influence tendency. The combined effect is very powerful and should be paid more attention. At last part the spectral analysis method is used to discuss the influence of the coupling calculation method.
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1. Introduction

Nuclear power system can be used as the heat source for hydrogen generation, such as high temperature cooling reactor (Schulten, 1980; Yalcin, 1989). Now china decided to develop the offshore nuclear power plant for island and offshore platform by electricity generation, sea water desalination and even hydrogen generation in the future. Hydrogen generation from water using nuclear energy is one of the solutions for this problem (Yamawaki et al., 2007; Forsberg, 2003). However, when the operation environment is ocean the coupling effect must be studied deeply. The neutron-thermal-hydraulic coupling analysis can describe physical process really. The mass flow rates, fluid and wall temperatures, void fractions of each channel have conspicuous effects on the neutron physics under the parallel channel instability phenomenon. Meanwhile the variation of heating power affects the flow in the channels. If the system is under ocean condition the characteristics is very hard to be predicted. Hence the coupling effect of neutron-thermal-ocean must be investigated clearly. The single channel and multi-channel flow instabilities have been studied widely by experiment and computation (Babelli and Ishii, 2001; Boure and Bergles, 1973; Ambrosini, 2008; Fukuda, 1979a, b; Wu et al., 2006; Xia et al., 2010a,b, 2011; Guo et al., 2005; Xing et al., 2010; Huang et al., 2004; Li et al., 2008). The multi-channel system instabilities under motion condition have also been studied (Guo et al., 2008a,b,c; Guo, 2010). The research about neutron coupling instabilities in multi-channel system are limited (Zinzani et al., 2008; Munoz-Cobo et al., 2008; Uehiro et al., 1996; Der, 2005; Lin et al., 1998; Yun et al., 2011). However, the tri-coupling instability analysis including neutron, thermal-hydraulic and ocean condition is rare reported. Basically, these boundary conditions, such as ocean condition and neutron physics, make up the real operation environment and which will be analyzed in the paper by a new model.

2. Models

2.1. Parallel channel thermal-hydraulic model

The original thermal-hydraulic model was developed by Clausse (Der, 2005). Then the author developed this model to parallel channel system under ocean condition. Here only the final equations are given below and the detailed model and derivation process can be found in reference Guo et al. (2008a,b, 2010). The model can analyze the parallel channel flow instability. Then the following ocean condition and neutron kinetics model can be added on the model.

* Corresponding author.
E-mail address: guoyun79@ustc.edu.cn (Y. Guo).

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Nomenclature

A	cross-sectional area of the control volume, m^2 or amplitude, m
A^+	nondimensional cross-sectional area of the channel $A^+ = A/A_H$
C	delayed neutron precursor concentration
Eu	in this paper $\Delta Ps = \rho f u s2$, $Eu = \Delta Ps/\rho f u s2 = 1$
H	heater section
H_{jm}	the influence factor of j-th and m-th channels
h^+	nondimensional enthalpy = $(h - h_f)/[Q/(\rho_f A_{x-s} u_s)]$
K	loss coefficient
k_{eff}	the effective multiplication factor
L_H	the length of heater section
L_n	the neutron transport distance
M^+	nondimensional channel mass $M^+ = M/\rho_f L_H A_H$
N	the neutron flux of j-th channel $1/(cm^2 \cdot s)$
$N_{pch} = \frac{Q}{W}\frac{\upsilon_{fg}}{h_{fg}\upsilon_f}$	phase change number
$N_{sub} = \frac{h_f - h_i}{h_{fg}}\frac{\upsilon_{fg}}{\upsilon_f}$	subcooling number
p_H	heater perimeter, m
Q	total power, W
q''	power density, W/m^2
R	riser section;
$S(r, t)$	external neutron source, $1/cm^3$
t^+	nondimensional time, $t^+ = t/(L_H/u_s)$
u^+	nondimensional velocity, $u^+ = u/u_s$;
u_s	characteristic velocity, $= u_{i,n}$
W^+	nondimensional mass flow rate, $W/(\rho_f A_{Hi} u_s)$
Xe	equilibrium quality
z^+	nondimensional length, $z^+ = z/L_H$

Greek letter

λ	delayed neutron precursors decay constant
λ^+	nondimensional boiling boundary $\lambda^+ = \lambda/L_H$
λc	decay constant of delayed neutron fraction
α	void fraction
β	delayed neutron fraction
ρ	reactivity
Λ	fast neutron generation time, $\Lambda = l_0/\kappa_{eff}$
ρ^+	nondimensional density, $\rho^+ = \rho/\rho_f$
$\wedge_{1\varphi}$	single phase region friction factor
$\wedge_{2\varphi}$	two-phase region friction factor;
$\delta x = (x - \bar{x})/\bar{x}$	for variable x, $\bar{x}$ represents the time averaged value
$\Omega = \frac{q'' p_H}{A_H}\frac{v_{fg}}{h_{fg}}$	intermediate variable
υ_f	specific volume of saturated liquid, $m^3\ kg^{-1}$
υ_{fg}	difference in specific volume of saturated liquid and vapor, $m^3\ kg^{-1}$

subscript

j	channel number
n	nth node in single phase region
i	inlet of channel
e	exit of heater section

$$
\begin{cases}
\frac{dL^+_{n,j}}{dt^+} = 2u^+_{i,j} - 2N_s\frac{N_{Zu,j}}{N_{sub,j}}(L^+_{n,j} - L^+_{n-1,j}) - \frac{dL^+_{n-1,j}}{dt^+} \\
\frac{dM^+_{H,j}}{dt^+} = u^+_{i,j} - \rho^+_{e,j}u^+_{e,j} \quad j = 1,\ 121 \\
\frac{d\rho^+_{e,j}}{dt^+} = \left\{\left[1 + \frac{\rho^+_{e,j}\ln(\rho^+_{e,j})}{1-\rho^+_{e,j}}\right]\frac{d\lambda^+_j}{dt^+} + \rho^+_{e,j}u^+_{e,j} - u^+_{i,j}\right\}\frac{(1-\rho^+_{e,j})^2}{(1-\lambda^+_j)[1-\rho^+_{e,j}+\ln(\rho^+_{e,j})]} \\
\frac{dM^+_R}{dt^+} = \frac{A_R}{A_H}u^+_e(\rho^+_e - \rho^+_R) \\
\frac{du^+_e}{dt^+} = \frac{du^+_i}{dt^+} - \Omega\frac{d\lambda^+}{dt^+} \\
\frac{du^+_{i,j}}{dt^+} = A_j\frac{du^+_{i,1}}{dt^+} + B_j, j = n \\
\frac{du^+_{i,1}}{dt^+} = \left(\frac{dW^+_{tot}}{dt^+} - \sum_{j=2}^{M}A^+_{H,j}B_j\right)\Big/\left(1 + \sum_{j=2}^{M}A^+_{H,j}A_j\right) \quad j = n \\
dW^+_{total}/dt^+ = 2\pi f^+ AW^+_{total,o}\cos(2\pi f^+ t^+)
\end{cases}
\tag{1}
$$

2.2. Ocean condition

The ocean condition is very complex. The same equivalent method used in reference (Guo et al., 2008a) is also adopted in this paper. All the motions, such as rolling, fluctuation and other motions which can change the total mass flow rate, can be processed the additional pressure drop. Hence, the ocean condition can be looked as nonlinear boundary condition.

2.3. Multi-Point reactor model

A neutron physical model was brought out to analyze the influences of neutron feedback (Uehiro et al., 1996). The spirit of the model is using the point model in each flow channel and the channel to channel effect weight is decided by the distance. Compared with three dimensional model the model is insufficient in reflect the spatial effect. However, present model can reflect the influence of neutron feedback qualitatively and the calculation speed is very fast. The results based on the model can be referenced. The normalized multi-point model is as follows:

$$
\frac{dN^+_j}{dt^+} = \frac{L_H}{u_s}\left[\frac{\rho_j + H_{jj} - \beta - 1}{\Lambda}N^+_j + \frac{\beta}{\Lambda}C^+_j + \frac{\rho_j}{\Lambda} + \sum_{m\neq j}^{M}\frac{H_{jm}}{\Lambda}\frac{N_{m0}}{N_{j0}}N^+_m + \sum_{m\neq j}^{M}\left(\frac{1}{\Lambda_m} - \frac{1}{\Lambda_j}\right)\frac{H_{jm}N_{m0}}{N_{j0}}\right] j = 1,\ 121 \tag{2}
$$

$$
\frac{dC^+_j}{dt^+} = \frac{L_H}{u_s}\lambda_c(N^+_j - C^+_j) \quad j = 1,\ 121 \tag{3}
$$

$$
\begin{aligned}
\rho_{j,new} &= \rho_{j,old} + \Delta\rho_j \\
&= \rho_{j,old} + C_{\alpha,j}(\alpha_{j,new} - \alpha_{j,old}) + C_{D,j}(T_{F,j,new} - T_{F,j,old})
\end{aligned}
\tag{4}
$$

where: $N^+_j = \frac{N_j - N_{j0}}{N_{j0}}$, $t^+ = \frac{t}{L_H/u_s}$, $C^+_j = \frac{C_j - C_{j0}}{C_{j0}}$

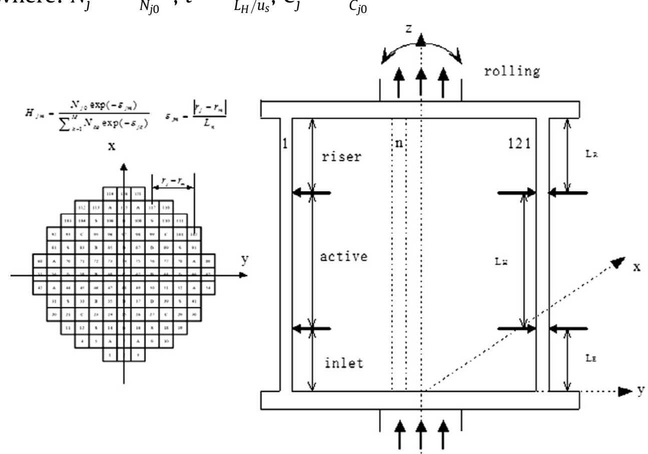

Fig. 1. The schematic of the reactor core, parallel channel thermal-hydraulic model and multi-point model.

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