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The development and validation of a thermal hydraulic code in rolling motion

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ABSTRACT

An advanced thermal hydraulic code is established on the basis of RELAP5/MOD3.3 code for the investigation of the thermal hydraulic behavior of nuclear power systems. The RELAP5 code is modified by adding a module calculating the effect of rolling motion and introducing new flow and heat transfer models. The experimental data are used to validate the theoretical models and calculation results. It is shown that the advanced flow and heat transfer models could correctly predict the frictional resistance and heat transfer coefficients in rolling motion. The thermal hydraulic code is used to simulate the operation of a natural circulation system in rolling motion. The calculation results are in good agreement with experimental data. The relative discrepancies between calculation results and experimental data are less than 5%.

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1. Introduction

In recent years, there has been a growing interest in a barge mounted floating nuclear desalination plant to provide potable water in coastal areas. Such plants are cost effective when compared with land-based nuclear power plants, have lesser construction periods and the potential to shift to any place, and have simplified anti-seismic design measures and decommissioning technology (Panov et al., 1998).

The main difference from a fluid mechanics point of view between a land-based and barge-mounted equipment is the influence of sea wave oscillations on the latter (Zhong et al., 2009). The thermal hydraulic behavior of barge-mounted equipment is influenced by different motions such as rolling, pitching and heaving (Figs. 1 and 2). Oscillations change the effective forces acting on the fluid and induce flow fluctuations, which results in a change in momentum, heat and mass transfer characteristics (Pendyala et al., 2008a,b). A series of single-phase natural circulation experiments were carried out by Murata et al. (2002) and Ishida and Yoritsune (2002), for analyzing the effect of rolling motion on the thermal hydraulic characteristics of reactor. Their results indicate 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 Ishida et al. (1990) also investigated the thermal hydraulic behavior of a marine reactor in ship motions. Their results indicate that the loop flow rate oscillate with rolling motion. While the core flow rate exhibits a change with rolling frequencies and correlated with the Reynolds number of rolling motion. On the basis of three dimensional temporal and spatial neutron dynamics and thermal–hydraulic models, the operational analysis platform for nuclear machineries under ocean conditions was established by Yu et al. (2008). This platform was used to investigate the operational characteristics of nuclear machinery under ocean environment such as rolling, heaving and heeling. Tan et al. (2009a,b) also carried out a series of experiments to study the single-phase natural circulation flow, heat transfer and two phase instability under rolling motion condition. They also obtained a empirical correlation for the single phase heat transfer according to their experimental data. However, their works are only limited to their experiments and the extrapolation is very limited.

In ocean environment, the flow oscillates periodically due to the effect of additional force. The flow and heat transfer is also different from that in no ocean environment. Until now, the theoretical models for the flow and heat transfer in ocean environment are not closed. Usually, the laminar flow can be analyzed by establishing mathematical models (Yan et al., 2010a,b,c). However, as for the turbulent flow, it is more complex and difficult to be described with mathematical methods. Because of these causes, the investigation of nuclear reactor thermal hydraulic characteristics in ocean environment and available results are limited.

RELAP5/MOD3 code has been developed for best estimate transient simulation of light water reactor coolant systems during postulated accidents where thermal–hydraulic phenomena are predominant (RELAP5 Development Team, 1995). The code models the coupled behavior of the reactor coolant system and the core for loss-of-coolant accidents and operational transients such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. A generic modeling approach is used that permits simulating a variety of thermal hydraulic systems. Control

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Nomenclature

A	flow area (m^2)
a_r	steady component of additional acceleration (m/s^2)
a_o	oscillation component of additional acceleration (m/s^2)
a	heat diffusion coefficient (m^2/s)
dm	mass of fluid particle (kg)
$DISS_i$	phasic energy dissipation term (W/m^3)
F	force (N)
g	gravitational acceleration (m/s^2)
H	height (m)
h	heat transfer coefficient ($W/(m^2\,K)$)
h_i^*	phasic enthalpy associated with bulk interface mass transfer (J/kg)
h_i'	phasic enthalpy associated with wall interface mass transfer (J/kg)
k	thermal conductivity (W/m K)
L	distance from the fluid to rolling axis (m)
n	rolling angle frequency ($=2\pi/T$)
Nu	Nusselt number
Pr	Prandtl number
p	pressure drop (Pa)
Q_i	interface heat transfer term (W/m^3)
Q_{wi}	phasic wall heat transfer rate (W/m^3)
Re	Reynolds number
r	radius (m)
T	rolling period (s)
T^*	fluid temperature (°C)
T'	fluctuating temperature (°C)
t	time (s)
U	internal energy (J/kg)
u', v'	fluctuating velocity (m/s)
v	velocity (m/s)
X_n	non-condensable quality
x, y, z	coordinate position (m)

Greek letters

α	void fraction
β	angular acceleration (rad/s^2)
δ	film thickness (m)
η	constant
λ	frictional resistance coefficient
μ	dynamic viscosity ($N\,s/m^2$)
ρ	density (kg/m^3)
θ	rolling angle (rad)
υ	kinematic viscosity (m^2/s)
ω	angular velocity (rad/s)
Γ_i	liquid, vapor generation term ($kg/s\,m^3$)
Γ_w	vapor generation term due to wall heat transfer ($kg/s\,m^3$)

Superscripts

$\rightarrow$	vector

Subscripts

0	initial
a	additional
f	friction
g	gravity
i	$=l,v$ for liquid and vapor, respectively
l	liquid
loc	local
m	maximum

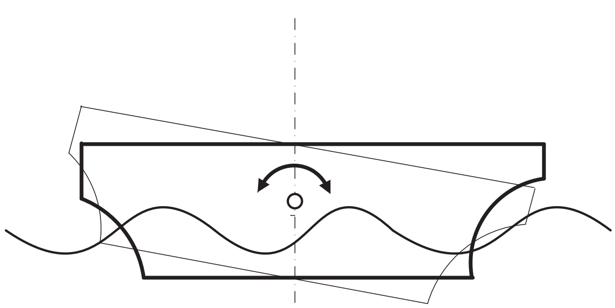

Fig. 1. Rolling motion.

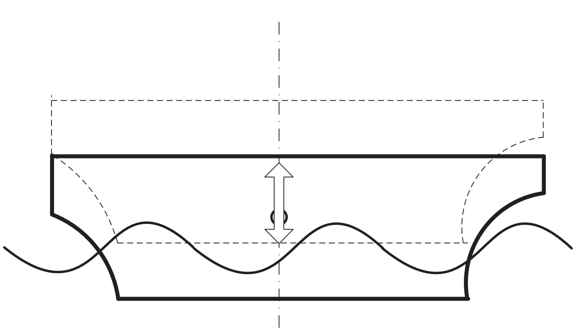

Fig. 2. Heaving motion.

system and secondary system components are included to permit modeling of plant controls, turbines, condensers, and secondary feed-water system.

In the present paper, an advanced thermal hydraulic code in rolling motion is established on the basis of RELAP5/MOD3.3 code. The code is modified by adding a module calculating the effect of rolling motion and introducing new flow and heat transfer models. A new condensation heat transfer model and a new matrix inverse calculating method are also adopted. The experimental data are used to validate the theoretical models and the advanced code.

2. Theoretical models

The RELAP5/MOD3 code, developed for best estimate simulations of transients in light water reactor coolant systems, is based on a non-homogeneous and non-equilibrium model for two-phase fluid set of equations. The solution is obtained through a partially implicit numerical scheme (RELAP5 Development Team, 1995). In this paper, the thermal hydraulic code is established on the basis of RELAP5/MOD3.3 code by modifying the momentum-conservation for liquid and vapor phases and intruding new flow and heat transfer models in rolling motion.

2.1. Field equations

The field equations include mass-conservation equations and energy-conservation equations for non-condensable gas mass, vapor mass, liquid mass and momentum-conservation equations. In ocean environment, the flow is affected by the additional force, which is shown in Fig. 3. The effect of additional force is analyzed in the momentum equations. The other conservation equations are

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