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ASSESSMENT OF MARS CODE FOR FLUID-TO-FLUID METHOD ON CHF UNDER HEAVING CONDITION

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ABSTRACT

Marine reactor system must have different characteristics in comparison with land-based nuclear power plant. One of the differences is the acceleration of system which is affected by ship motion such as heaving, rolling and pitching. The critical heat flux (CHF) of the marine reactor core can be dramatically changed under oscillating conditions. Thus, it is important to predict CHF of marine reactor having the heaving motion in order to increase the safety of the reactor. Otsuji et al. found that CHF ratio was proportional to the 1/4th of acceleration factor. In this paper, only the heaving condition is considered to evaluate acceleration effects on the CHF. To verify this characteristic, the fluid scaling methods suggested by Coffield, Katto and Ahmad were used to compare Otsuji's Freon CHF data with CHF correlations for water in the system code. MARS code was used to analyze scaled water data from Otsuji's data. As a result, the variation of the acceleration affects flow conditions such as the mass flow rate, void fraction and so on. The results show that the CHF decreases with oscillating the gravity acceleration in a vertical direction, which is in good agreement at each condition with previous studies reported.

INTRODUCTION

The most prominent characteristic of marine reactor from land-based reactor is that it should be operated during voyage over the ocean. Furthermore the ocean has the most dynamic motion such as heaving, rolling and pitching. In particular, the heaving is one of the most important factors to the variation of CHF. Thus, a prediction of CHF characteristic is an important matter of marine reactor design and has been considered over the past long period. The main purpose of this study was to verify the relationship between the CHF and acceleration in the heaving condition and to assess capability of MARS code using the fluid to fluid scaling between R-113 and water. To analyze the result of experiment data, followed Otsuji's experiment procedure and model [1]. However, there was a critical problem to apply experimental data to water-based marine reactors since the data was obtained from R-113 flow. Therefore, a fluid to fluid modeling should be used to examine the applicability of the MARS code to simulation of moving motions for marine reactors.

NOMENCLATURE

a, Δg	[m/s^2]	Gravity acceleration
A	[-]	Amplitude of oscillation
L	[m]	Length
D	[m]	Diameter
F	[-]	Scaling factor
g	[m/s^2]	Gravity
G	[kg/m^2 s]	Mass flux
k	[W/m K]	Thermal conductivity
q	[W/m^2]	Heat flux
t	[sec]	Time
C_p	[kJ/kg s]	Heat capacity
H_{lg}	[kJ/kg]	Latent heat of vaporization
ΔH_{in}	[kJ/kg]	Inlet subcooling
Y_{min}	[-]	Nondimensional flow speed ratio at minimum inlet velocity

Special characters

ρ	[kg/m^3]	Density
μ	[Pa s]	Dynamic viscosity
σ	[N m]	Surface tension
ψ	[-]	Modeling parameter
ω	[-]	Oscillation frequency
γ	[m^2/N]	$\left.\partial(\rho_l/\rho_g)/\partial P\right\|_{saturation}$

Subscripts

L	Liquid phase
g	Vapor phase
CHF	Critical heat flux
W	Water
M	Model
0	Steady state

BACKGROUND

Critical Heat Flux and Acceleration

The critical heat flux is the heat flux at which boiling crisis occurs and a sudden deterioration of heat transfer rate occurs. Thus, CHF is the most important factor in design of nuclear reactor, boiler and so on. However, the mechanism of CHF is not completely clear yet. In the field of marine reactor, various reports have been published on this study over a long period of time. In particular, these reports considered the relation of acceleration and CHF. So far, even though some CHF correlations contained a gravity term, each correlation has some limitation of application range. CHF experiments with the gravity change have been performed by the several researchers such as Chang, Isshiki and Otsuji.

Chang et al. [2] proposed a CHF correlation including the acceleration effect. When the marine heaves, the net of the coolant flow velocity would decrease, and bring down the CHF. Also, when the marine is in up-motion, the fluid acceleration in the direction of gravity would increase, and the lift pressure drop would increase, too. The ratio of CHF under oscillating to steady state CHF is proportional to the 1/4th level of the ratio of gravity acceleration to earth gravity and can be expressed as follows:

$$q_{CHF} / q_{CHFO} = \left(g / g_o\right)^{1/4} \tag{1}$$

Isshiki et al. [3] studied the CHF under periodically changing gravity fields using a small water loop operated at atmospheric pressure. The experiments were conducted under both natural and forced circulation with a void fraction of more than 1.5% at the exit. The results are expressed as follows:

$$q_{CHF} / q_{CHFO} = 1 - \left(1 - y_{\min 0.8}\right) \Delta g / g_o \tag{2}$$

where $y_{\min 0.8}$ is the ratio of the minimum inlet velocity at $\Delta g = 0.8 g_o$ to the inlet velocity at $\Delta g = g_o$.

Otsuji et al. [1] performed a series of single channel experiments with R-113 using a thermo-hydraulic loop capable of vertical movement. It was shown that the CHF decreased quantitatively with oscillating gravity acceleration in a vertical direction. As a result, the CHF values obtained by equation (1) were smaller than almost all of the experimental data, irrespective of quality and subcooling. Low limit of the CHF ratio was suggested as follows:

$$q_{CHF} / q_{CHFO} = \left(1 - \Delta g / g_o\right)^n \tag{3}$$

where n is a constant which is dependent both on subcooling and the mass flow rate at the inlet. As values increase, the value of n increases and asymptotes to 0.25. Figure 1 shows the variation of CHF ratio according to various gravity acceleration and the comparison of above correlations.

Critical Heat Flux in the MARS Code

MARS code can predict the CHF in rod bundle with tube data such as the AECL-UO CHF lookup table method by Groeneveld et al. [4]. The table was set up by using 14,402 data from vertical tube. After finding the CHF from the table, a multiplying factors (chfmul) shown in Equation (4) are used to compensate the differences of the geometry heated length, bundle geometry, spacer grid, heat flux profiles, low flow condition and so on, because the table is made from tube data normalized to a tube inside diameter of 0.008 m.

$$\mathrm{CHF} = \mathrm{CHF}_{\mathrm{table}} \times \mathrm{chfmul} \tag{4}$$

Therefore, the multiplying factors should be applied to allow the table's use in other sized tube which has different hydraulic diameter, heated length, and so on. In this study, the factors specified in the code were used in the MARS analysis.

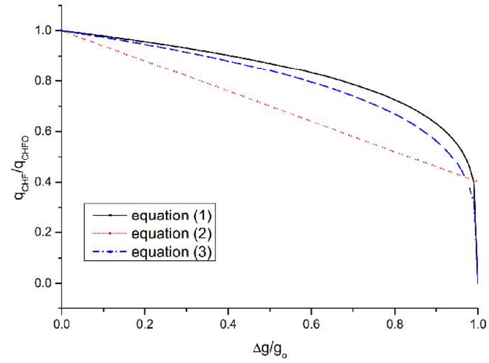

Figure 1 CHF ratio for reduced gravity acceleration

MODELING AND CODE ANALYSIS

Fluid-to-fluid Modeling

In this paper, the main objective is to show the characteristics that the CHF is decreased with an increase of acceleration, and to evaluate the possibility of using the CHF data from Otsuji's experiment with R-113 for CHF estimation by the MARS code for the marine application. However, since the MARS code is based on water data, needed a fluid-to- fluid modeling between R-113 and water. There are many methods to deduce the fluid-to-fluid modeling of CHF data, which were suggested by Ahmad [5], Katto [6] and Coffield [7].

In general, three basic similarities are required for a fluid-to-fluid modelling, namely

Geometric similarity: $$\left(\frac{L}{D}\right)_W = \left(\frac{L}{D}\right)_M \tag{5}$$

Hydrodynamic similarity: $$\left(\frac{\rho_l}{\rho_g}\right)_W = \left(\frac{\rho_l}{\rho_g}\right)_M \tag{6}$$

Thermodynamic similarity: $$\left(\frac{\Delta H_{in}}{H_{lg}}\right)_W = \left(\frac{\Delta H_{in}}{H_{lg}}\right)_M \tag{7}$$

where subscript '*W*' denotes the equivalent value for water and subscript '*M*' indicates the modelling fluid, respectively. In addition to the above basic similarities, a mass flux similarity is needed, i.e., the fluid-to-fluid modelling also requires the same dimensionless mass flux for both fluids as an additional hydrodynamic similarity.

Ahmad [5] proposed a fluid-to-fluid scaling with the compensated distortion model using nondimensional parameter matrix affecting on CHF for the boiling heat transfer. Ahmad deduced 13 dimensionless numbers shown in Equation (5), which are based on the dimensional analysis and a lot of experimental data.

$$f(q_{CHF}, G, \Delta H_{in}, L, D, g, H_{lg}, \rho_l, \rho_g, \mu_l, \mu_g, C_{Pl}, C_{Pg}, k_l, k_g, \sigma, \gamma, \beta) = 0 \quad (8)$$

He chose seven important dimensionless groups for CHF by applying Buckingham's Pi theorem to the dimensionless equation was expressed as

$$\frac{q_{CHF}}{GH_{lg}} = f\left(\psi_{Ahmad}, \frac{\Delta H_{in}}{H_{lg}}, \frac{\rho_l}{\rho_g}, \frac{L}{D}\right) \quad (9)$$

where ψ_{Ahmad} can be presumed to be the modelling parameter for a dimensionless mass flux

$$\psi_{\text{Ahmad}} = \Lambda_1 \Gamma_1^{4/3} \Gamma_2^{1/5} \quad (10)$$

where $\Lambda_1 = \frac{GD}{\mu_l}$, $\Gamma_1 = \frac{\mu_l}{(\sigma D \rho_l)^{1/2}}$, $\Gamma_2 = \frac{\mu_l}{\mu_g}$

A Generalized correlation of CHF for flow boiling in a vertical tube developed by Katto [6] was expressed by the following dimensionless groups:

$$\frac{q_{CHF}}{GH_{lg}} = f\left(\frac{G\sqrt{D}}{\sqrt{\sigma\rho_l}}, \frac{\Delta H_{in}}{H_{lg}}, \frac{\rho_l}{\rho_g}, \frac{L}{D}\right) \quad (11)$$

The dimensionless group $G(D/\sigma\rho_l)^{1/2}$ was recommended as the modelling parameter for fluid-to-fluid modelling,

$$\psi_{\text{Katto}} = \frac{G\sqrt{D}}{\sqrt{\sigma\rho_l}} \quad (12)$$

Coffield [7] proposed a scaling factor technique which was successful for CHF modelling in the subcooled boiling flow. He also derived a dynamic similitude from dimensional analysis which was based on CHF relationship originally suggested by Barnett [8] as,

$$q_{CHF} = f(L, D, G, \frac{\rho_l}{\rho_v}, \Delta H_i, H_{lg}, C_{pl}, k_l, \gamma) \quad (13)$$

According to dimensionless analysis using above parameters, he made dimensionless parameters and expressed modeling parameter as,

$$\frac{q_{CHF}\gamma^{1/2}}{H_{fg}\rho_f^{1/2}} = F\left(\frac{L}{D}, \frac{DC_{pf}\rho_f^{1/2}}{k_f\gamma^{1/2}}, \frac{G\gamma^{1/2}}{\rho_f^{1/2}}, \frac{\rho_f}{\rho_g}, \frac{\Delta H_i}{H_{fg}}\right) \quad (14)$$

$$\psi_{\text{Coffield}} = G\sqrt{\frac{\gamma}{\rho_l}} \quad (15)$$

Otsuji's Experiment

Otsuji et al. had performed an experiment using a forced circulation loop which was operated with R-113 as a working fluid. In the test section, the outer diameter and the tube thickness of the heater were 10 and 0.5 mm, respectively. The heater type was a SUS 304 and the total length was 1.3 m. The following test conditions were considered: pressure of 3 bar, inlet subcooling of 1 to 60 K, mass flux of 510 and 980 kg/m^{2}s, and acceleration of 0 to 0.5g. They conducted experiments for two cases with the different heaving conditions using vertical moving loop and artificially the inlet mass flow rate variation. The results of both cases showed quite good coincidence each other within the scattering range of the experimental data. Thus, it is concluded that that could be used the inlet mass flow rate variation as an input variable to simulate the vertical acceleration in MARS assessment.

Scaling Procedure and MARS Nodalization

In order to study the effect of acceleration on CHF, three author's scaling procedures were used to make input data of MARS code as described in the previous section. The conditions for dynamic similitude can be obtained by using dimensional analysis of hydrodynamic behaviour. From equation (5), Geometric similarity related to L and D can be neglected by using same geometric conditions. Therefore, the code nodalization was made according to Otsuji's test section as shown in Figure 2.

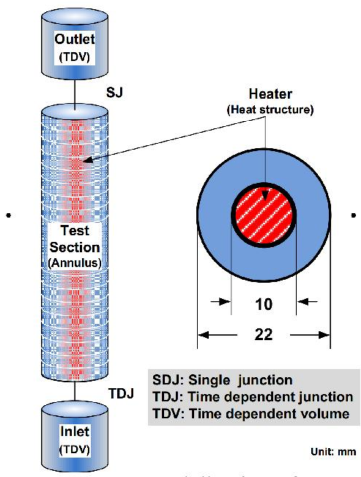

Figure 2 MARS nodalization of test section

The following procedures were performed to convert the thermal and physical CHF properties from the R-113 fluid to the water fluid.

(1) Calculate the density ratio of the liquid to the vapour. Find out the pressure at which the density ratio of R-113 is equal to that of water.

$$\left(\frac{\rho_l}{\rho_g}\right)_{R113} = \left(\frac{\rho_l}{\rho_g}\right)_{Water} \quad (16)$$

(2) Calculate the mass flux scaling factor (F_G) at the equivalent pressure as follows:

- Coffield

$$F_G = \frac{G_{Water}}{G_{R113}} = \left(\frac{\gamma_{R113}}{\gamma_{Water}}\right)^{1/2} \left(\frac{\rho_{l,\ Water}}{\rho_{l,\ R113}}\right)^{1/2} \quad (17)$$

- Katto

$$F_G = \frac{G_{Water}}{G_{R113}} = \frac{\left(\sqrt{\sigma \rho_l}\right)_{Water}}{\left(\sqrt{\sigma \rho_l}\right)_{R113}} \quad (18)$$

- Ahmad

$$F_G = \frac{G_{Water}}{G_{R113}} = \left(\frac{\Gamma_{1R113}}{\Gamma_{1Water}}\right)^{4/3} \left(\frac{\Gamma_{2R113}}{\Gamma_{2Water}}\right)^{-1/5} \left(\frac{\mu_{lWater}}{\mu_{lR113}}\right)$$

(19)

(3) Calculate the latent heat scaling factor ($F_{\Delta H}$) as latent ratio of water to R-113 as follows:

$$F_{\Delta H_i} = \frac{\Delta H_{i,\ Water}}{\Delta H_{i,\ R113}} = \frac{H_{lv,\ Water}}{H_{lv,\ R113}} \quad (20)$$

(4) Calculate the CHF scaling factor by multiplying the latent scaling factor and the mass flux scaling factor as follows:

$$F_{CHF} = F_G \cdot F_{\Delta H_i} \quad (21)$$

(5) Calculate the CHF from the CHF scaling factor as follows:

$$\left(q_{CHF}\right)_{Water} = F_{CHF} \times \left(q_{CHF}\right)_{R113} \quad (22)$$

In the step (1), the pressure of water used on code input is 24.6 bar when the ratio of liquid-vapor density is 69.53. Fluid to fluid modeling with properties and result of scaling factors shown in Table 1 and 2. Finally the CHF for water corresponding to Otsuji experiment with Freon can be obtained by multiplying and compared with CHF calculated by MARS.

Since MARS code cannot simulate the motion effect, a sinusoidal inlet flow variation was used as input corresponding to the gravity variation with form of

$$g(t) = g_o\left(1 + A\sin(\omega t)\right) \quad (23)$$

where A and ω are the amplitude and the frequency of the oscillation, respectively. Figure 3 shows water inlet flow variation according to gravity, which represents the water inlet flow variation in Otsuji's experiment.

Figure 4 illustrates the almost linear dependency of the fluctuation of inlet mass flux on the acceleration variation in the heaving condition of Otsuji's experiment, which will be used to determine the mass flux fluctuation of water according to acceleration in MARS code analysis with following process.

Table 1 Properties of R-113 and water

Property	Freon R-113	Water
P [bar]	2.94	24.06
T_{sat} [°C]	85.23	223.64
ρ_l / ρ_v [-]	69.53	69.53
H_{lv} [J/kg]	131822.94	1847906.75
μ_l [Pa s]	3.50e-04	11.99e-05
μ_v [Pa s]	1.15e-05	16.56e-06
k_l [W/mK]	0.05	0.64
$C_{P,l}$ [kJ/kg K]	1.02	4.63
γ [cm²/N]	2.40	0.30

Table 2 Comparison with results of scaling methods

	Otsuji experiment	Coffield model	Katto model	Ahmad model
P [bar]	3	24.06	24.06	24.06
G [kg/m²s]	510	1109.94	676.36	1002.74
	980	2132.83	1299.68	1926.84
F_G [-]	-	2.18	1.33	1.96
$F_{\Delta H_i}$ [-]	-	14.02	14.02	14.02
F_{CHF} [-]	-	30.51	18.59	27.56
CHF [kW/m²]	247	7535.97	4591.73	6807.80

Since MARS code cannot simulate the motion effect, a sinusoidal inlet flow variation was used as input corresponding to the gravity variation with form of

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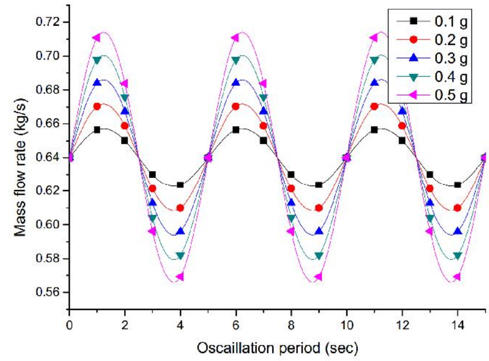

Figure 3 Inlet flow oscillation on code input for various acceleration (980 kg/m²s, 20 K, Katto)

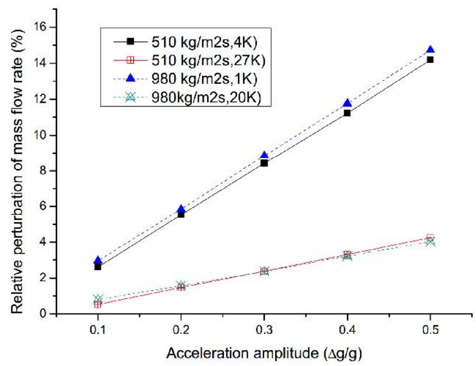

Figure 4 Perturbation of mass flow rate according to the acceleration

RESULTS AND DISCUSSION

The results from code analysis using scaling method suggested by Ahmad, Katto and Coffield show a good trend of CHF ratio for gravity acceleration as shown in Figures 5 through 8. In these scaling method, geometric similarity was the same with Otsuji's experimental test section, thus the main considerations were the mass flux scaling factor, F_G, the latent heat scaling factor, $F_{\Delta H_i}$ and CHF factor, F_{CHF}. As a matter of fact, the vertical moving reactor is affected by time-dependent gravity acceleration with heaving.

However, as mentioned previously, the inlet flow oscillation with the corresponding frequency and amplitude under the heaving condition was used to analyze because there is no option of changing acceleration in MARS code. MARS results are compared to water-scaled CHF data by three authors' method in figures 5 through 8. The calculated result which is applied Coffield modeling shows a reasonably good agreement with experimental data at 510 kg/m^{2}s of mass flux and 4 K of inlet subcooling. Ahmad modelling technique is useful for 510, 980 kg/m^{2}s and 27, 1 K of mass flux and inlet subcooling. Katto method predicts well for 980 kg/m^{2}s of mass flux and 20K of subcooling.

The results in Figures 9 represent that the ratio of the CHF under oscillating condition to the steady (non-oscillating) CHF decreases as the inlet subcooling increases. Especially, at around 20 and 27 K of subcooling, the amount of decrease becomes maximum, which was also observed in the experiment. As the inlet subcooling increases at a given mass flux, the CHF ratio reduction comes close to proportional to 1/4th power of gravity.

The CHF decreases quantitatively with the oscillation of gravity acceleration in a vertical direction as the previous researches concluded. As results, the CHF for water in the scaling calculation, multiplied by CHF scaling factor to CHF for R-113, was nearly similar to results from MARS code within maximum 13.78 % error and 7.59 RMS, which are tabulated in table 3.

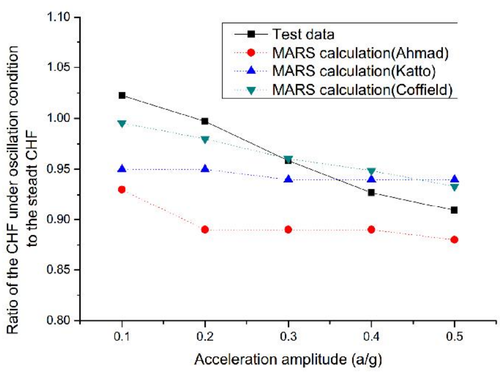

Figure 5 Similarity comparison with R-113 and water (G: 510 kg/m^{2}s, Inlet subcooling: 4K)

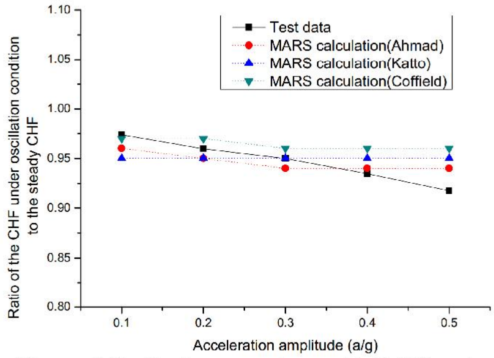

Figure 6 Similarity comparison with R-113 and water (G: 510 kg/m^{2}s, Inlet subcooling: 27K)

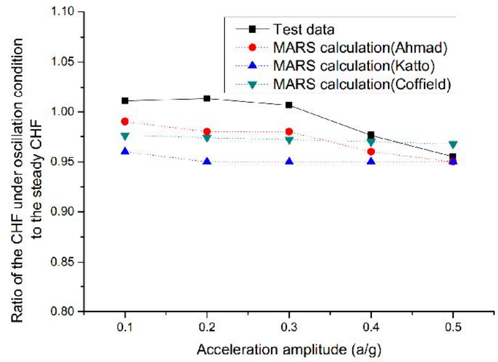

Figure 7 Similarity comparison with R-113 and water (G: 980 kg/m^{2}s, Inlet subcooling: 1K)

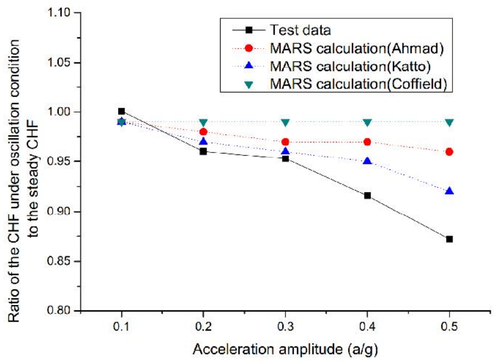

Figure 8 Similarity comparison with R-113 and water (G: 980 kg/m^{2}s, Inlet subcooling: 20K)

Table 3 Prediction* errors and RMS**

	510 kg/m^{2}s					
	4K			27K		
	Ahmad	Katto	Coffield	Ahmad	Katto	Coffield
0.1g_o	-9.52	-7.40	-2.65	-1.88	-2.72	-0.70
0.2g_o	-10.73	-5.16	-1.73	-1.16	-1.28	0.63
0.3g_o	-7.04	-1.47	0.22	-0.59	-0.37	1.53
0.4g_o	-4.08	1.72	2.35	0.85	1.33	3.15
0.5g_o	-2.86	3.59	2.63	2.22	3.45	5.02
RMS	7.48	4.46	2.12	1.48	2.14	2.77

	980 kg/m²s					
	1K			20K		
	Ahmad	Katto	Coffield	Ahmad	Katto	Coffield
$0.1g_o$	-2.11	-5.15	-3.42	-1.04	-0.65	-0.82
$0.2g_o$	-3.22	-5.77	-3.85	1.71	1.13	3.31
$0.3g_o$	-2.57	-5.57	-3.42	2.01	1.00	4.11
$0.4g_o$	-1.56	-2.72	-0.67	5.79	4.22	8.33
$0.5g_o$	-1.04	-0.44	1.31	10.23	4.96	13.78
RMS	2.23	4.44	2.84	5.41	3.01	7.59

$$^{*}\ \text{Error} = \frac{\text{Value}_{\text{pred}} - \text{Value}_{\text{exp.}}}{\text{Value}_{\text{exp.}}}$$

$$^{**}\ \text{RMS error} = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n} \text{Error}_i^2}$$

CONCLUSION

When the reactor suffers from heaving in the ocean, the mass flow rate and void fraction might change vertically, and thus can seriously affect on CHF. Therefore, the Freon-based CHF data from Otsuji's experiment was compared by applying the Ahmad, Katto and Coffield modelling parameters to extend its applicability on the water-based analysis and design. Also assessed the thermal-hydraulic system code for land-base reactor design, MARS, with an artificially fluctuation of the inlet flow rate to have a same effect on gravity acceleration change. The following conclusion can be drawn the present paper:

1. The Coffield modeling parameter shows a reasonably good agreement with experimental data at 510 kg/m²s of mass flux and 4K of inlet subcooling.
2. The Ahmad modelling technique is useful for 510, 980 kg/m²s and 27, 1K of mass flux and inlet subcooling.
3. The Katto method predicts well for 980 kg/m²s of mass flux and 20K of subcooling.

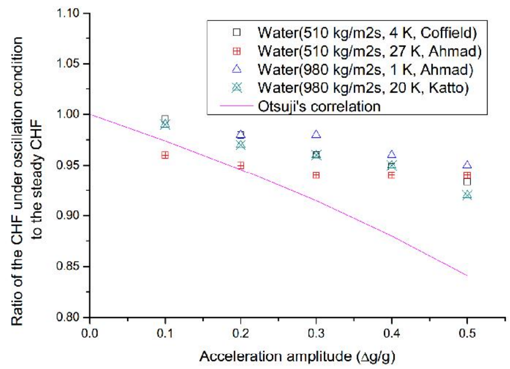

Figure 9 Reduction of water CHF ratio under oscillating condition

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