Analysis of CHF under Oscillatory Flow Conditions using MARS-KS for Marine Reactor Application

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1. Introduction

Recently, the International Maritime Organization (IMO) has addressed an environmental regulation to decrease total greenhouse gas emissions from ships by 50% compared to 2008 emissions by 2050 [1]. Consequently, domestic and foreign shipbuilders are actively researching the development of carbon-free ships using nuclear energy.

The MIT [2] research team proposed a design concept for an offshore floating nuclear power plant (OFNP) that can withstand damage from earthquakes and tsunamis, and ROSATOM [3] has already commenced commercial operation of Akademic Lomonosov, Russia's first floating offshore nuclear power plant, to supply electricity to isolated areas. Seaborg [4] has also proposed a modular CMSR (Compact Molten Salt Reactor) barge design with a capacity of 200 MW to 800 MW of electricity and a 24-year operating life. In Korea, KEPCO E&C [5] has designed a small nuclear reactor BANDI-60, KAERI [6] is developing a light water marine nuclear power plant ARA, and UNIST [7] is developing MicroURANUS, a lead-bismuth cooled marine nuclear power plant.

Marine nuclear power plants differ from conventional nuclear power plants in that they can incline and oscillate due to marine waves and wind, and therefore, the safety analysis methods used for land-based nuclear power plants need to be improved. Rolling, heaving, and flow oscillation can occur, and it is necessary to determine which of these phenomena has a greater impact on accidents. As a result, development studies of the MARS-KS for a marine nuclear reactor have been conducted [8, 9], and critical heat flux (CHF) phenomena under inclined, rolling, and heaving conditions have been analyzed using the moving reactor model [10].

Following this process, the present study aims to validate the ability of the MARS-KS to predict CHF under oscillatory flow conditions. The experimental database of Zhang et al. [11] was selected for the validation.

2. Results

2.1 CHF experiments under oscillatory condition by Zhang et al.

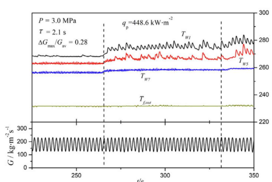
Zhang et al. [11] conducted CHF experiments in vertical tubes under oscillatory flow conditions using deionized water as a working fluid and the detailed experimental conditions are presented in Table I. The test section comprised a vertical tube with a total length of 1620 mm, an inner diameter of 6 mm, and a thickness of 2 mm. A central heating region of 720 mm was surrounded by non-heating regions of 450 mm each at the inlet and outlet. A unique feature of the experimental loop was an oscillator that could produce reverse flow at the inlet when the large flow oscillation motion occurs.

During the experiment, they gradually increased the heat flux and observed that the wall temperature fluctuated along the inlet sine flow curve long before CHF, which is a phenomenon known as periodic dryout. Based on this phenomenon, they defined two parameters: q_P, which represents the periodic dryout heat flux at the onset of wall temperature fluctuation, and q_C, which is the heat flux at the CHF point. The CHF point is determined when the wall temperature curve rapidly increased by 5 to 20 s and did not fall back. They compared these two heat flux values with the stable CHF (q_S) and established two normalized values, F_P (q_P/q_S) and F_C (q_C/q_S).

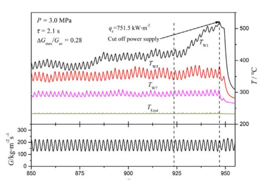
They found that F_C showed almost constant values, similar to stable values, regardless of the increase in the ratio of mass velocity ($\Delta G_{max}/G_{av}$). In contrast, F_P decreased as $\Delta G_{max}/G_{av}$ and the oscillation period (τ) increased, as presented in Figure 5 and 6.

Table I: Zhang et al.'s experimental condition

Pressure (MPa)	1.0, 2.0, 3.0
G_{av} (kg/m-s^2)	255, 355, 455
ΔT_{sub} (°C)	55
$\Delta G_{max}/G_{av}$	0 - 3.0
τ (s, period)	1.04, 2.1, 5.2, 10.6



(a) Start of periodic dry out



(b) CHF

Fig. 1. Zhang et al.'s transient wall temperature data with an increasing heat flux [11]

2.2 MARS-KS Analysis

In the MARS-KS simulation, the vertical pipe with a heat structure was nodalized as shown in Figure 2, and the cases at pressure 1.0 MPa and flow rate 255 kg/m^2-s were presented. The simulation included an inlet sinusoidal flow and a gradual increase of heat flux, similar to the experimental setup. In order to compare the MARS-KS results with Zhang et al.'s, two normalized values, F_P and F_C, were evaluated based on the stable

CHF calculated by MARS-KS. As in the experiment, the MARS-KS results showed both periodic dryout and CHF, as illustrated in Figure 3.

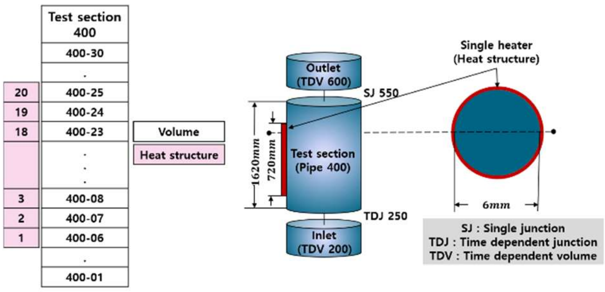


Fig. 2. MARS-KS nodalization of Zhang et al.'s experiment

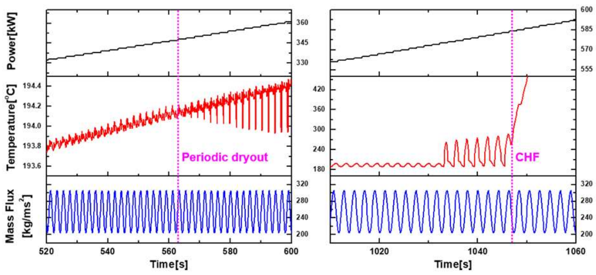


Fig. 3. Periodic dryout and CHF in MARS-KS result

To determine the consistent temperature oscillation criteria for the periodic dryout heat flux, three different temperature fluctuation cases were compared. These cases included the heat flux at the onset of small-scale temperature oscillation on the wall ($\Delta T_{wall} \sim 0.1°C$), the heat flux when $\Delta T_{wall} \geq 1$ °C, and the heat flux when $\Delta T_{wall} \geq 2$ °C. The results (Figure 4) showed that the difference in periodic dryout heat flux was not varied significantly depending on the three criteria. However, large temperature fluctuations of over 2 °C were observed within a very short time period in cases with longer τ. Therefore, $\Delta T_{wall} \geq 1$ °C was selected as the criteria for the onset of periodic dryout heat flux. Additionally, the CHF was determined when the wall temperature failed to recover after a rapid increase, similar to the experiment.

Figures 5 and 6 depict the results of both F_P and F_C from the MARS-KS simulation based on $\Delta G_{max}/G_{av}$ and τ. The MARS-KS code significantly under-predicted F_P values compared to the experiment although the overall trend of F_P with $\Delta G_{max}/G_{av}$ and τ can be reproduced. A previous study [12] has suggested that periodic dryout is related to the thickness of the liquid film on the wall. As the mass flux increases or τ decreases, the thickness of the liquid film increases due to the enhanced liquid transport along the axial direction. However, the flow regime predicted by MARS-KS at the CHF point was an inverted annular flow regime, indicating that the liquid film on the wall was completely dryout. It is speculated that MARS-KS has limited capabilities in simulating the local liquid film behavior resulting in fast dryout of the liquid film and it may cause under-prediction of the results.

Furthermore, it was found that MARS-KS also predicted lower F_C than the actual experimental values. However, the change of F_C with respect to $\Delta G_{max}/G_{av}$ was insignificant, similar to the experiment. Nevertheless, a slight increase in F_C was observed when $\Delta G_{max}/G_{av}$ exceeded 1.0, which is attributed to the reverse inlet flow. This is supported by the rapid change of the void fraction near the CHF at the outlet as shown in Figure 7, which could be the reason for the difficulty in accurately predicting the CHF point.

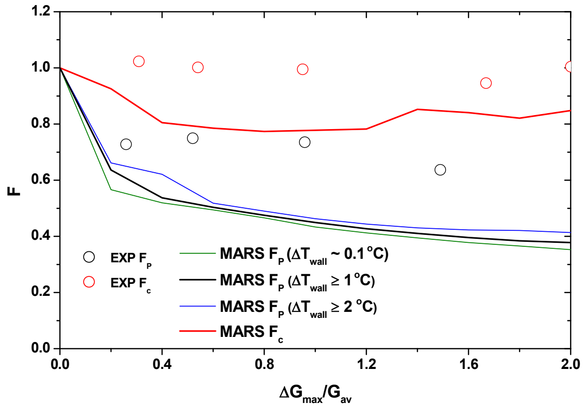


Fig. 4. The difference of F_P depending on amplitude of wall temperature (τ = 1.04)

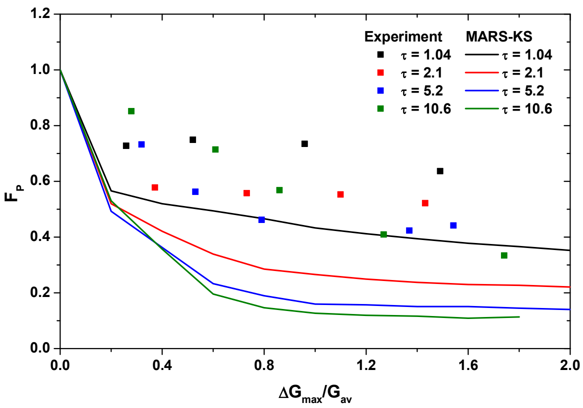


Fig. 5. The comparison of periodic heat flux

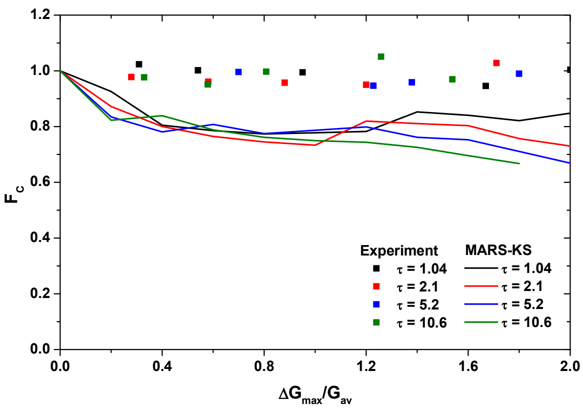


Fig. 6. The comparison of critical heat flux

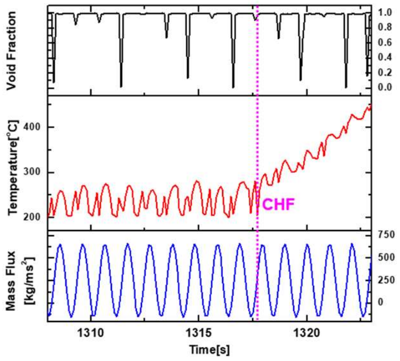


Fig. 7. Void fraction near the CHF (τ = 1.04 s, $\Delta G_{max}/G_{av} = 1.6$)

3. Conclusions

In this study, CHF under oscillated flow conditions was analyzed using MARS-KS considering marine reactor application. MARS-KS can reproduce overall trends of the periodic dryout and CHF but significantly under-predicted them than the experimental data. This implies that the current version of MARS-KS may provide a conservative result in predicting CHF under flow oscillation. The reason for this is attributed to the CHF models and relevant closure relations proposed under steady-state inlet flow conditions.

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