Preliminary Study on Thermal Margin of External Reactor Vessel Cooling Using MARS-KS1.4 Code with Newly Implemented CHF Correlations

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1. Introduction

The critical heat flux (CHF) on a downward-facing hemisphere dominates the thermal margin of external reactor vessel cooling (ERVC) for in-vessel core melt retention at the lower head of the reactor vessel. Since most thermal-hydraulic system codes have been proved to provide generally high-fidelity predictions on two-phase natural circulation flows, they are suitable for evaluating the transient circulation flow rate and the corresponding CHF on a lower head. Unlike the severe accident analysis codes, however, these thermal-hydraulic system codes do not incorporate a proper CHF model for the downward-facing hemisphere

In this study, three CHF correlations were newly implemented into the MARS-KS1.4 code, a domestic safety analysis code adopted by regulatory authorities. Note that two of them were selected as they could take into account the effect of the mass flux on the CHF, which was not the case for most proposed models. The modified MARS-KS code was applied to simulation of external reactor vessel cooling of the APR1400. The transient behavior of critical heat flux and the heat transfer mode on a lower head surface with the highest heat flux were presented.

2. CHF Models

2.1 Selected Correlations

The ULPU is the well-known full-scale experimental facility to investigate the limit of coolability for the in-vessel retention concept of AP600 or AP1000. Among five test programs, ULPU-III employed an inclined plain baffle (thermal insulation) around the lower head of the reactor vessel, and its measurement data of the CHF was conservative than subsequent test data. The CHF correlation from the ULPU-III test was expressed only as a function of the polar angle on the hemisphere as [1]:

$$q''_{CHF} = 490 + 30.2\theta - 8.88 \cdot 10^{-1} \theta^2$$
$$+ 1.35 \cdot 10^{-3} \theta^3 - 6.65 \cdot 10^{-5} \theta^4 \qquad (1)$$

A recent experimental study on the CHF for in-vessel retention was carried out by Toshiba Energy Systems & Solutions Corp. The CHF was measured in a rectangular test section as shown in Fig. 1, and the effect of various parameters such as pressure, mass flux, thermodynamic quality, inclination angle on the CHF was investigated. The suggested correlation (Let's call it Toshiba correlation hereafter.) of CHF in kW/m^2 is expressed as function of pressure (P) in MPa, mass flux (G) in kg/m^{2}s, thermodynamic quality (x), and the inclination angle (θ) as the following [2]:

$$q''_{CHF} = -3626.79P^2 - 2.45025 \cdot 10^{-4} G^2$$
$$- 434757x^2 + 0.0610736\theta^2 + 2263.69P$$
$$+ 0.914268G - 14657.4x + 0.300264\theta$$
$$+ 35.5521P\theta - 2.30392 \cdot 10^{-3} G\theta \qquad (2)$$
$$+ 136.071x\theta + 0.0152043PG - 1993.24Px$$
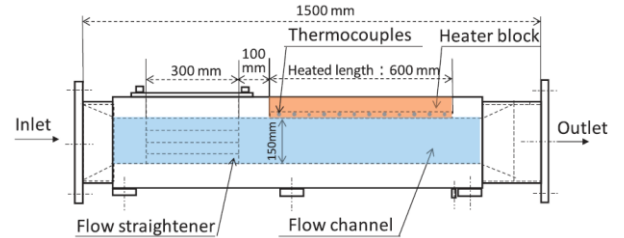$$- 6.65384Gx - 88.0463$$

Fig. 1. Schematics of the test section in the recent Japanese CHF experiment for in-vessel retention

The last selected correlation was derived from the conventional SULTAN program. The SULTAN facility also adopted a rectangular channel, and covered a wide range of forced convection experimental parameters. Based on 191 CHF data, the following correlation was proposed [3]:

$$q''_{CHF} = A0(E,P,G) + A1(E,G) \cdot x$$
$$+ A2(E) \cdot x^2 + A3(E,P,G,X) \cdot \theta \qquad (3)$$
$$+ A4(E,P,G,X) \cdot \theta^2$$

where E denotes the gap in m. Details of coefficients in Eq. (3) are found in [3]. Note that both the Toshiba correlation and the SULTAN correlation account for the effect of the mass flux by natural circulation.

2.2 Implementation into MARS-KS1.4

Three subroutines for the above CHF correlations were added to source files of the MARS-KS1.4 code. Users are supposed to choose a convective boundary condition type in the inputs for heat structures so that the associated the heat transfer coefficient can be obtained from the embedded heat transfer package. As listed in Table 1, geometry types with difference options for the CHF correlations were added; 190 for ULPU-III correlation, 191 for Toshiba correlation, and 192 for SULTAN correlation.

Table I: Modified convection boundary type

Index	Geometry type	
1, 100, 101	Default	
…	…	
135	Helical S/G shell side	
190	Downward -facing hemisphere	**ULPU-III** correlation
191		**Toshiba** correlation
192		**SULTAN** correlation

3. MARS-KS Simulation

3.1 MARS-KS model

The flow path of cooling water established when the reactor vessel is externally flooded was modelled via one-dimensional nodes as shown in Fig. 2. The gap channel between the lower head of the reactor vessel and the insulation, to which the heat load from the molten core is applied, was modelled with three pipe components, and heat structures were connected to them.
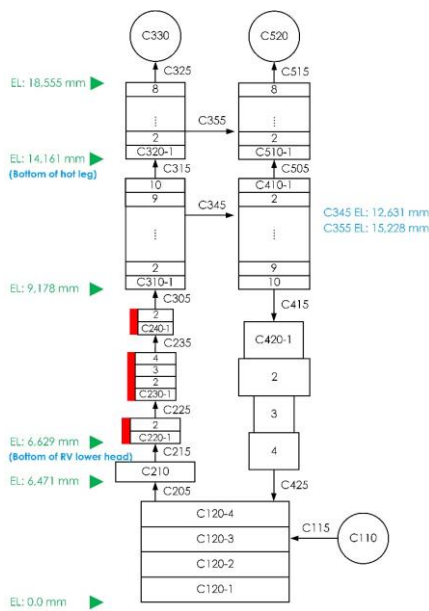

Fig. 2. Nodalization of the natural circulation flow channels during ERVC [4]

As the boundary condition at the outlet, the reactor containment pressure was assumed to 2.5. The heat flux profile calculated by the analytical two-layer model was imposed on the ex-vessel wall of the lower head, bringing the total heat load to cooling water to 23.3 MW. It was assumed the operator starts to supply the cooling water into the lower part of the reactor cavity using the boric acid makeup pump (BAMP) as soon as the collapsed water level is reduced below a prescribed value in order to prevent the depletion of cavity water.

The loss coefficient at dominant minor loss points in MARS-KS inputs was estimated based on CFD analysis at the single-phase liquid state before significant void generation [4].

3.2 Calculation results

The transient behaviors the natural circulation flow rate is in Fig. 3. As the temperature of cooling water approaches to the saturation temperature and significant vapor bubbles are generated, the transition into the two-phase flow regime occurred at about 2,100 sec. During the transition, a considerable oscillation of the flow rate is observed. Then, the natural circulation flow rate increases drastically, and its mean value is sustained at around 900 kg/s.

The surface heat flux on the lower head and the critical heat flux predicted by implemented correlations at C240-2 are plotted in Figs. 4 and 5. Note that, in the transient accompanied by a sharp fluctuation of the free convective flow rate, the surface heat flux on the lower head is not necessarily equal to the heat flux from the inner wall by the molten core. In particular, it is predicted that a drastic and instantaneous rise of the surface heat flux occurs when the transition into two-phase flow regime begins and the flow rate oscillates significantly.

When the CHF is predicted by ULPU-III correlation or SULTAN correlation, the boiling regime is changed to the post-DNB region as shown in Fig 6, which indicates that the coolability achievable by ERVC may not be sufficient to ensure the in-vessel corium retention.
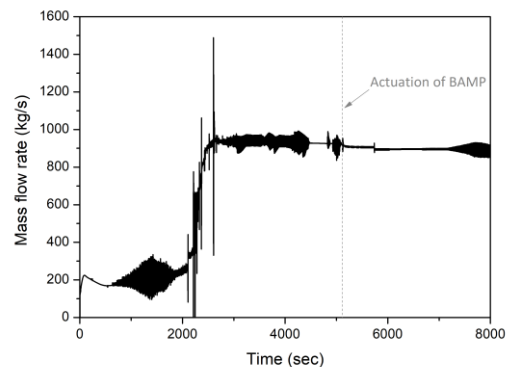

Fig. 3. Mass flow rate of cooling water at C205

However, the subcooled nucleate boiling regime is sustained if the Toshiba correlation is applied. It is revealed that, according to the selected CHF model for the downward-facing hemisphere, one can arrive at different conclusions about the thermal margin of ERVC.
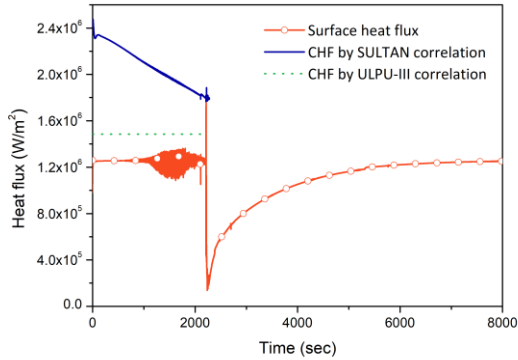

Fig. 3. Surface heat flux and the critical heat flux predicted by ULPU-III correlation and SULTAN correlation
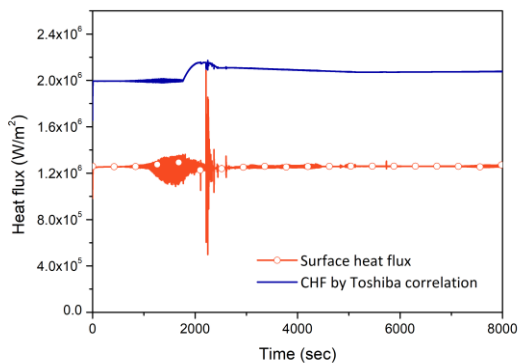

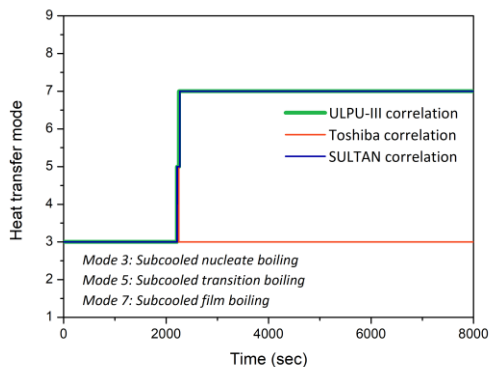Fig. 4. Surface heat flux and the critical heat flux predicted by Toshiba correlation

Fig. 5. Heat transfer mode according to the selected CHF correlation for ERVC

3. Conclusions

Three CHF correlations for the lower head of the reactor vessel was newly implemented into the MARS-KS1.4 code to better predict the thermal margin of ERVC of the APR1400. It was revealed that the surface heat flux may exceed the cooling limit when ULPU-III correlation or SULTAN correlation is selected. A further code modification to receive the input of the polar angle for heat structures will be conducted, and it is also required to investigate the adequacy of the logic to determine the heat transfer mode under transient conditions.

The modified MARS-KS code will be coupled with the smoothed-particle hydrodynamics (SPH) code, named SOPHIA, to provide a new analysis method for in-vessel retention of the molten-core debris [5].

Acknowledgement

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