CFD-aided Estimation of the Natural Circulation Flow Rate in External Reactor Vessel Cooling via 1-D Simulation Using MARS-KS

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1. Introduction

The external reactor vessel cooling (ERVC) is the severe accident management strategy adopted by the domestic power reactor APR1400 to retain and stabilize the molten core debris inside the reactor vessel as illustrated in Fig. 1. In a thermal-hydraulic view point, the thermal margin of ERVC is mainly determined by the critical heat flux (CHF) on the lower head of the reactor vessel. Given that the mass flux is one of the most crucial factors on the CHF, the natural circulation flow rate established around the reactor vessel and the insulation is closely associated with the thermal margin of ERVC.

While the system analysis code such as MARS-KS can provide robust predictions on most two-phase flow problems, its calculation result of a natural circulation flow may vary substantially relying on the way of user's modelling since the natural circulation is in general driven by very small pressure differences. On the other hand, commercial CFD codes have a higher fidelity in simulating the single-phase flow in channels with the complicated geometry, whereas its accuracy in the two-phase flow condition needs to be assessed.
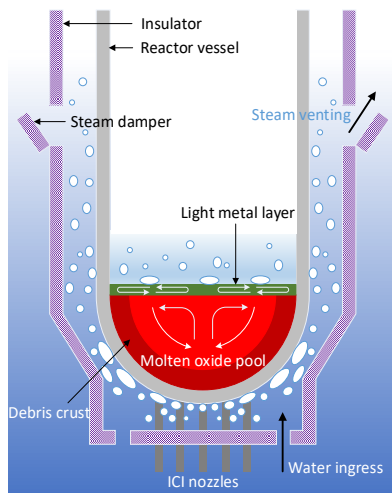

Fig. 1. Concept of in-vessel retention by means of ERVC

In this study, the natural circulation flow circuit of ERVC of APR1400 was modelled via the ANSYS-CFX code. Then the loss coefficient at dominant minor loss points in MARS-KS inputs was estimated based on the difference in the pressure drop between two codes before significant void generation. With applying the obtained loss coefficients in the single-phase liquid state, the evolution of thermal-hydraulic variables to the two-phase natural circulation flow conditions was simulated with the MARS-KS code.

2. CFD analysis

The flow channels of ERVC established between the reactor vessel, the insulation, and the reactor cavity wall were modelled as shown in Fig. 2. For computational efficiency, one fourth of the reactor vessel and other sections were drawn azimuthally. A total of 587,000 meshes were generated for the fluid volume.

The heat flux distribution on the lower head by the core melt was implemented as the boundary condition. And the reference pressure was set to 3.75 atm so that the fluid pressure at the top equals to the predetermined reactor containment pressure, 3.0 bar.

The heat transfer across the solid part and the natural circulation of the cooling water were calculated with ANSYS-CFX 17. The Shear Stress Transport (SST) model was applied as the turbulence model, and the Boussinesq model was chosen in evaluating the buoyance force in natural circulation flows caused by the density gradient.
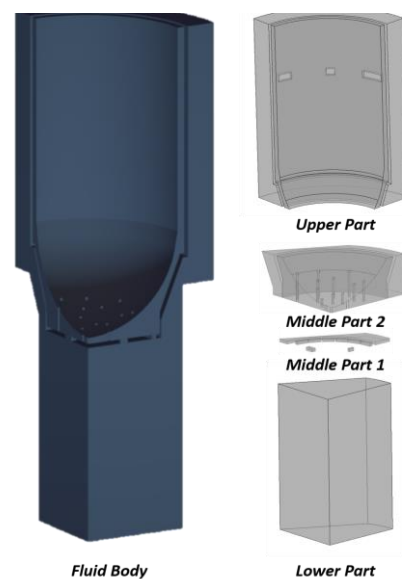

Fig. 2. Natural circulation flow channels around the reactor vessel modelled for CFD simulations

The calculated 3-D flow streamlines are shown in Fig. 3. According to the preliminary calculation with MARS-KS, a significant void begun to appear from the lower head when the inlet temperature of cooling water through the ingress door reached 383.1 K. Thus, this temperature was set to a point at which the comparison of pressure drops from both codes was conducted in the single-phase liquid state, and the loss coefficients were estimated. The calculation results from the CFD code revealed that the mass flow rate of natural circulation was about 240 kg/s at the moment when the cooling water temperature at the inlet reached 383.1 K.

Fig. 3. 3-D flow streamlines in the natural circulation circuit during ERVC simulated by the ANSYS-CFX code

3. Numerical simulation with MARS-KS

3.1. MARS-KS model

The flow path of cooling water was modelled via one-dimensional nodes as shown in Fig. 4. 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.

As the boundary condition at the outlet, the reactor containment pressure was assumed to 3.0 bar based on a preceding numerical research on containment transients of APR1400 under severe accident with GASFLOW [1]. The heat flux distribution according to the angle on the lower head was implemented identically as that found in [2], bringing the total heat load to cooling water to 23.3 MW. When the collapsed water level becomes lower than a predetermined elevation, cooling water from the IRWST was supposed to flow into the reactor cavity.

Initially, the cooling water was assumed to fill up to the bottom of the cold leg at the temperature of 48.9 °C. It was also assumed that the space above the water level was occupied with air at the same temperature.

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

3.2. Evaluation of loss coefficients

In the natural circulation channels of ERVC, the locations where substantial minor losses are expected include the ingress door at the bottom of the insulation, the egress door at the side wall of the simulation, and the downward flow channel between the narrowed reactor cavity and the lower portion of the insulation (C420 in Fig. 4).

In vertical junctions C205 and C420(2), the pressure drops from CFD and MARS-KS codes were compared, and its difference was assumed to the minor loss that has to be considered by the loss coefficient given in the input. Then, the loss coefficient at the egress door C345 was adjusted so that the natural circulation flow rate in the MARS-KS simulation could be the same as that obtained from the CFD code at the identical inlet temperature. The evaluated loss coefficients at three selected junctions were tabulated in Table I.

Table I: Loss coefficient at selected junctions

Junction	Flow area (m^2)	Loss coefficient
C205	1.81	4.25
C345	1.71	72.5
C420-2	3.96	62.4

3.3. Numerical result of two-phase natural circulation flow

The transient behaviors the natural circulation flow rate and the void fraction around the heated surface were plotted in Fig. 5. As the temperature of cooling water approached to the saturation temperature and

significant vapor bubbles were generated, the transition into the two-phase flow regime occurred at about 2,100 sec. Then, the natural circulation flow rate increases drastically as shown in Fig. 5(a). The mass flow rate exhibits oscillatory behavior in time, but its mean value was sustained at around 890 kg/s, which corresponds to the flow velocity of 0.53 m/s through the ingress door. The evolution of other thermal-hydraulic variables will be discussed in detail at the conference.
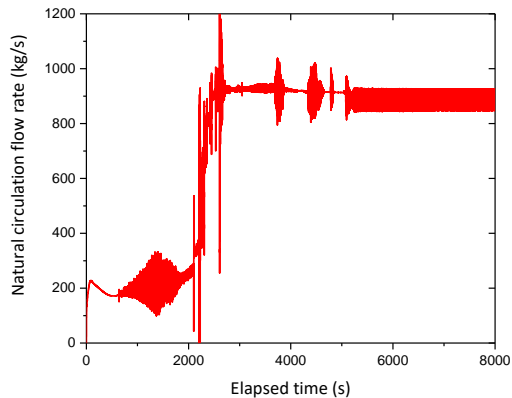
(a) Mass flow rate
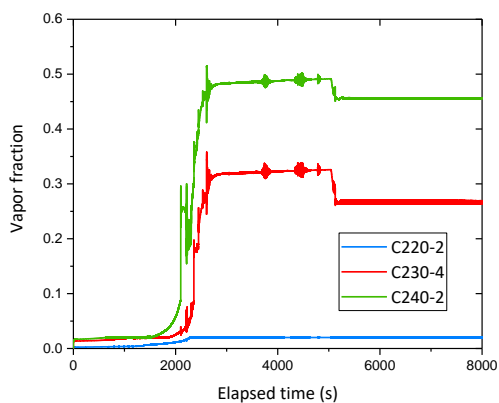
(b) Vapor fraction around the lower head

Fig. 5. MARS-KS calculation results of two-phase natural circulation flow during ERVC

Presented in Fig. 6 is the heat transfer mode evaluated by the MARS-KS code for the exterior surface of the upper section of the lower head, to which the maximum heat load is applied. It was revealed that, over the entire transient, the subcooled nucleate boiling regime was sustained by the two-phase natural circulation flow through the annular gap between the reactor vessel and the insulation. However, this problem has to be further investigated since the proper critical heat flux model for h is not implemented yet into the MARS-KS code; one needs to note that the value of the critical heat flux serves as a decisive factor in the logic for selection of heat transfer modes in the MARS-KS code.
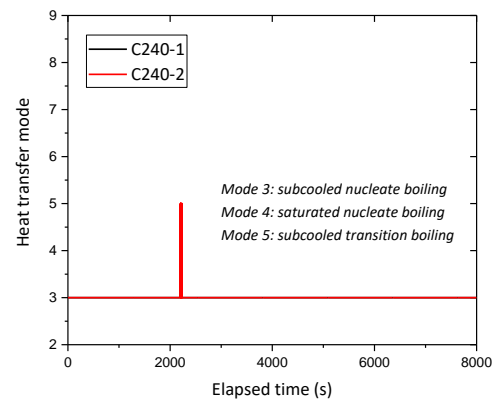

Fig. 6. Heat transfer mode on the lower head surface

4. Conclutions

The CFD-aided estimation of the natural circulation flow rate in ERVC was carried out via 1-D simulation using the MARS-KS code. This system analysis model on ERVC of APR1400 was developed for coupling with the smoothed-particle hydrodynamics (SPH) code, SOPHIA [3], to provide a new analysis method for in-vessel retention of the molten-core debris. Based on the meshless method, this SPH model simulates natural convection of the molten core and calculates imposed head loads without relying on empirical correlations. As a next step, the experimental database or the empirical correlation of the critical heat flux on a downward-facing hemisphere will be implemented into MARS-KS to better predict the thermal margin of the ERVC.

Acknowledgement

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