Development and Validation of CUPID Reactor Vessel Module

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1. Introduction

The simplified 3D approach where the 'cross-flow junctions' between 1D modules represent some multi-dimensional flow features was first developed in the system codes like RELAP and ATHLET codes. This may be sufficient in some cases particularly for porous body like a reactor core when only cross flows exist due to high resistance to transverse velocity. Explicit 3D modules exist as an option in the codes TRACE and CATHARE-3 for the reactor pressure vessel of which main objective is modelling of large scale 3D effects in a pressure vessel during LBLOCA such as ECCS water, reflooding of the core with transverse power profile effects. The 3D modules are straight forward extension of the 1D modules for cylindrical or Cartesian coordinates. A multiscale software platform, including a CFD module and CATHARE-3 as a system code, has been developed to model reactor pressure vessel effectively. SPACE code also started to develop 3D reactor core module using within 1000 cells.

After having developed 1D system analysis code, MARS, the Korea Atomic Energy Research Institute (KAERI) began to develop the CUPID code to address the need for a multi-dimensional analysis. In two-phase momentum equations, non-drag forces, such as lift, wall lubrication, and turbulent dispersion forces including turbulence and wall function are modeled in addition to the interfacial drag forces and these non-drag forces are selectively activated. These features with the capacity to deal with huge unstructured mesh over 10,000,000 may categorize CUPID as a CMFD distinguished from traditional system analysis code. The flow or heat structure coupling methodologies a system code, MARS, the reactor vessel module, and the steam generator module have been also developed to extend the application of CUPID as a 3D module of nuclear reactor.

In this paper, the recent development and validation of CUPID reactor vessel module, CUPID-RV, is presented.

2. Methods and Results

In this section CUPID reactor vessel module and the validation results are described. The reactor vessel module includes a reactor core bundle module including reflooding model and downcomer CFD module.

2.1 CUPID mathematical model

A set of two-fluid conservation equations[1], which is used in nuclear system analysis code, is adopted to establish CUPID-RV module.

$$\frac{\partial}{\partial t}(\alpha_g\rho_g)+\nabla\cdot(\alpha_g\rho_g\vec{u}_g)=\Gamma_v+\Gamma_{wall} \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_l\rho_l)+\nabla\cdot(\alpha_l\rho_l\vec{u}_l)=-\Gamma_v-\Gamma_{wall} \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_g\rho_g X_n)+\nabla\cdot(\alpha_g\rho_g X_n\vec{u}_g)=0 \tag{3}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{u}_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{u}_g\vec{u}_g\right)=-\alpha_g\nabla P+\nabla\cdot\left(\alpha_g\mu_{g,eff}\nabla\vec{u}_g\right)\\&+\alpha_g\rho_g\vec{g}+\overrightarrow{\mathrm{M}}_g^{mass}+\overrightarrow{\mathrm{M}}_g^{drag}+\overrightarrow{\mathrm{M}}_g^{non-drag}+\overrightarrow{\mathrm{M}}_g^{VM}+\overrightarrow{\mathrm{M}}_g^{WF}\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_l\rho_l\vec{u}_l\right)+\nabla\cdot\left(\alpha_l\rho_l\vec{u}_l\vec{u}_l\right)=-\alpha_l\nabla P+\nabla\cdot\left(\alpha_l\mu_{l,eff}\nabla\vec{u}_l\right)\\&+\alpha_l\rho_l\vec{g}+\overrightarrow{\mathrm{M}}_l^{mass}+\overrightarrow{\mathrm{M}}_l^{drag}+\overrightarrow{\mathrm{M}}_l^{non-drag}+\overrightarrow{\mathrm{M}}_l^{VM}+\overrightarrow{\mathrm{M}}_l^{WF}\end{aligned} \tag{5}$$

$$\begin{aligned}&\frac{\partial\left(\alpha_g\rho_g e_g\right)}{\partial t}+\nabla\cdot\left(\alpha_g\rho_g e_g\vec{u}_g\right)=-P\frac{\partial\alpha_g}{\partial t}-P\nabla\cdot\left(\alpha_g\vec{u}_g\right)\\&+\nabla\left(\alpha_g\vec{q}_g\right)+\frac{P_s}{P}H_{ig}\left[T^s\left(P_s\right)-T_g\right]+\Gamma_v h_g^*\\&-\left(\frac{P-P_s}{P}\right)H_{gf}\left(T_g-T_l\right)+q''_{g-p}A_{g-p}\end{aligned} \tag{6}$$

$$\begin{aligned}&\frac{\partial\left(\alpha_l\rho_l e_l\right)}{\partial t}+\nabla\cdot\left(\alpha_l\rho_l e_l\vec{u}_l\right)=-P\frac{\partial\alpha_l}{\partial t}-P\nabla\cdot\left(\alpha_l\vec{u}_l\right)\\&+\nabla\cdot\left(\alpha_l\vec{q}_l\right)+H_{if}\left[T^s\left(P_s\right)-T_l\right]-\Gamma_v h_f^*\\&+\left(\frac{P-P_s}{P}\right)H_{gf}\left(T_g-T_l\right)+q''_{l-p}A_{l-p}\end{aligned} \tag{7}$$

$$\rho_p\frac{\partial T_p}{\partial t}=k\nabla T_p+S_p \tag{8}$$

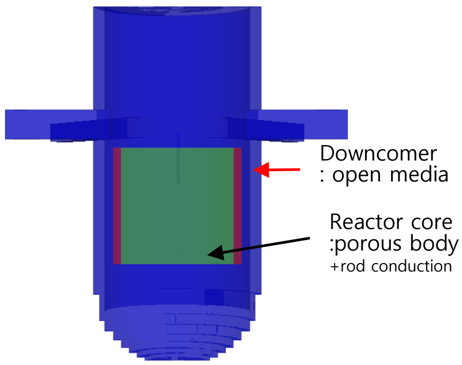

Fig.1 Concept of CUPID-RV module

2.2 Reactor core module

The reactor core module of CUPID-RV is a pack of interfacial heat and momentum transfer model based on a vertical flow regime of Fig. 2, a wall heat transfer model from rod to fluid by the boiling curve, and a wall friction model in a rod bundles. In the calculation, the heat conduction equation is solved at first for a solid rod bundle in a cell, and then, $q''_{k-p}A_{k-p}$ and $\overrightarrow{\mathrm{M}}_k^{WF}$ are calculated using rod surface temperature and rod surface area, channel hydraulic diameter. After that, local void fraction and vertical velocity are used for determining flow regime, and then, $\overrightarrow{M}_k^{drag}$, H_{ik} are calculated according to the flow regime.

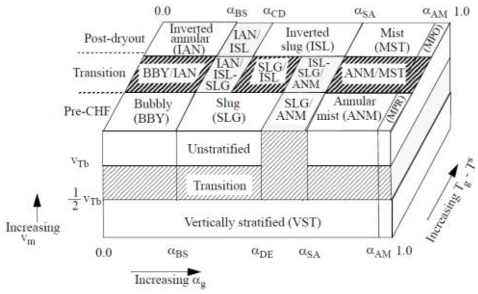

Fig.2 Vertical flow regime map of CUPID[2]

2.3 Reflood model

The key model of the LBLOCA reflood stage is rezoning a heated rod, as shown in Fig. 3, to find out a precise quench front where the transition and film boiling heat transfer correlation from rod to fluid should be changed, for example, from Chen's to Weismann's. As to reflood experiments, the quench front region is known to be relatively narrow at within 15~20cm, and therefore, rezoning a heated rod is essential for reflood mode.

For the interfacial model, the weber numbers and minimum value related to the diameter of droplets or bubbles are adjusted for the reflood stage, and then, the interfacial heat transfer and friction terms are changed from the non-reflood to reflood stage.

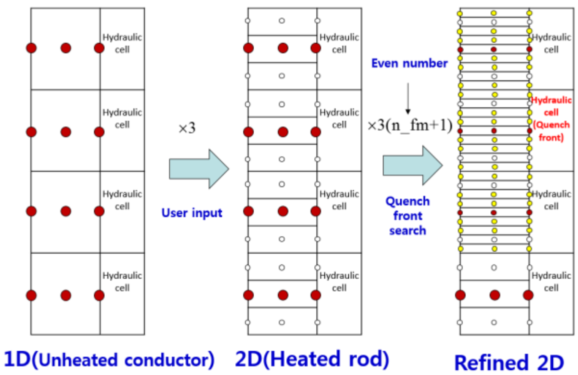

Fig. 3 Rezoning concept for reflood model

2.4 Downcomer module

CUPID-RV treats downcomer as an open media because there is no rod bundle. q''_{k-p} A_{k-p} and $\overrightarrow{M}_k^{WF}$ are not used, and Eq. (8) is neglected in this region. The interfacial transfer terms of $\overrightarrow{M}_k^{drag}$ and H_{ik} are calculated based on the topology map concept which is generally used in CFD code after Tentner proposed it. The turbulence model is used here in dowcomer related to the effective viscosity, $\mu_{k,eff}$ of Eq. (4) and (5).

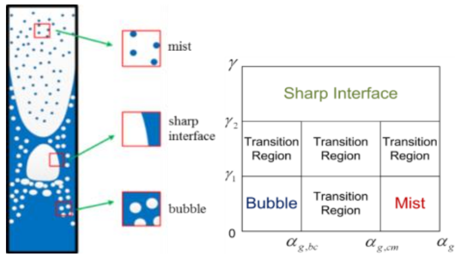

Fig.4 Topology map concept for CFD code[3]

2.4 Validation against FLETCHT-SEASET 31701

In order to validate CUPID-RV reactor core module for two-phase flow phenomena in the reflood stage of PWR LBLOCA, the FLECHT SEASET 31701[4] test were simulated. This test is for Westinghouse 17x17 rod bundle which has the same heating length as benchmark PWR. The test section was geometrically modelled using 20 cells of 0.125x0.125x0.183 m as shown in Fig. 5. The heated rod surface temperatures at three locations of 0.61 m, 1.82m, and 3.05m are compared to experimental results in Fig. 5, and it indicates that CUPID-RV reactor core modules including reflood model is implemented properly in CUPID-RV.

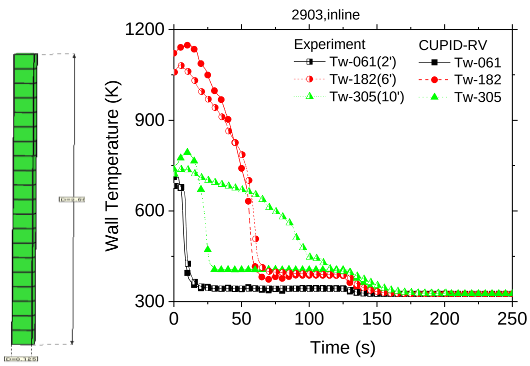

Fig. 5. Comparison of wall temperature transient between CUPID-RV and experiments.

2.5 Validation against UPTF

The simulation of UPTF 201/III [5], in which 493, 487, 489 kg/s ECC flows for 1, 2, 3 cold legs, 102 kg/s steam flow, and 942 kg/s ECC delivery flow were measured as shown in Fig. 6, was conducted to validate downcomer analysis capability of CUPID-RV. Initially, topology-based interfacial drag is used, but it turned out to provide much high drag coefficient and the ECC delivery is underestimated. The interfacial drag was replaced with the one based on traditional flow regime map, and then, the ECC delivery and downcomer pressure become similar to MARS calculation results. The slight difference of ECC delivery mass flow rate seems to be induced by the discrepancy in downcomer flow regime between CUPID-RV and MARS. It must be noted that the interfacial drag model was implemented only for vertical flow regime in CUPID-RV.

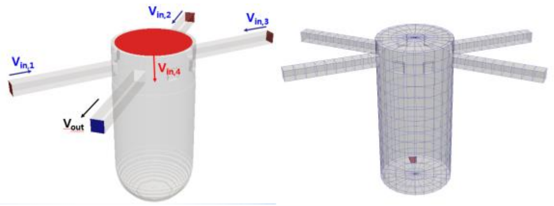

Fig. 6. UPTF test concept and calculation mesh.

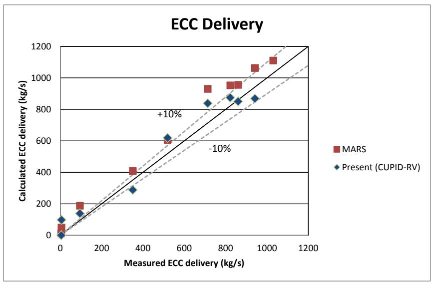

Fig. 7. Comparison of ECC delivery mass flow rate between CUPID-RV and MARS.

3. Conclusions

In this paper, recent development and validation of CUPID reactor vessel module, CUPID-RV, is briefly discussed. A pack of interfacial and wall heat and momentum transfer model including reflood model was implemented, and two calculations for FLECHT SEASET 31701 and UPTF 201/III were conducted to validate CUPID-RV capability for LBLOCA reflood in rod bundles and ECC delivery in downcomer. The calculation results indicates that reactor core module seems to be implemented properly though the further validations should be done before it is applied to reactor calculation.

ACKNOWLEDGEMENTS

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