Development of Severe Accident Containment Analysis Package

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1. Introduction

In the event of severe accident of the nuclear power plant, the containment undergoes continuous changes of the thermal-hydraulic conditions due to increasing steam generated by the fuel decay heat and the non-condensable gases such as hydrogen produced by oxidation of the metallic materials. The pressure, the temperature, the gas composition of the local regions of the containment would have different conditions and tendencies compared with those of other regions. In safety viewpoint, the pressure and temperature of the containment is the important parameters, of course, the local hydrogen concentration is also the parameter of the major concern because of its flammability and the risk of the detonation. In addition, there are possibilities of occurrence of other relevant phenomena following the reactor core melting such as DCH(direct containment heating) due to HPME(high pressure melt ejection), steam explosion due to fuel-coolant interaction in the reactor cavity and molten core-concrete interaction at the late stage.

It is important to predict the containment responses during a severe accident by a reasonable accuracy for establishing of effective mitigation strategies and preparation of the safety features required. For this purpose, Korean utility, research institute and universities have utilized the existing SA code such as MAAP code[1] developed by FAI and EPRI, US, and MELCOR code[2] developed by Sandia National Lab. and USNRC. Along the way, the necessity of development of the domestic code have increased gradually to avoid the limitations related to intellectual propriety originated from using oversea-developed computer codes. Thus, in Korea, there have been an extensive efforts to develop the computer code which can analyze the severe accident behavior of the pressurized water reactor. The development has been done in a modularized manner and SACAP(Severe Accident Containment Analysis Package) code is now under final stage of development. SACAP code adopts LP(Lumped Parameter) model and is applicable to analyze the synthetic behavior of the containment during severe accident occurred by thermal-hydraulic transient, combustible gas burn, direct containment heating by high pressure melt ejection, steam explosion and molten core-concrete interaction.

In this paper, the overview of the SACAP development status is presented and brief introductions to a number of SA phenomena analysis modules are included.

2. Development of the SA containment analysis module

2.1 Thermal-Hydraulics Analysis Module

The thermal-hydraulics analysis module is the firstly developed one and it comprises the frame of SACAP. It has been developed based on the pre-developed containment safety analysis code for DBA(design basis accident) scope, CAP(Containment Analysis Package)[3]. For establishing the SA containment TH module, the basic conservation equations of CAP were modified partly, the NCG(Non-condensable gases) species were expanded and a number of constitutive models were added for wall heat transfer. Although the basic equation is based on the lumped-parameter concept as other SA codes, the resolution of the analysis can be manipulated by user's nodalization scheme.

Currently, V&V (Verification & Validation) is under process and a number of ISP(International Standard Problem) experiments were simulated by SACAP. In this paper, the SACAP analysis results for ISP-35 NUPEC[4] and ISP-47 TOSQAN[5] are presented including comparison with other existing NPP simulation codes as shown in Fig.1 ~ Fig 3. As a result of simulation, SACAP predicts well the thermal-hydraulic variables such as temperature, pressure and NCG concentration.

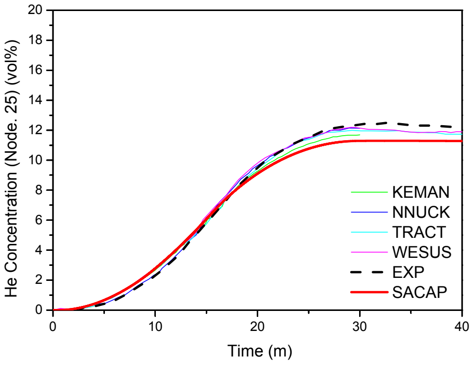

Fig. 1. He concentration of dome node in ISP-35

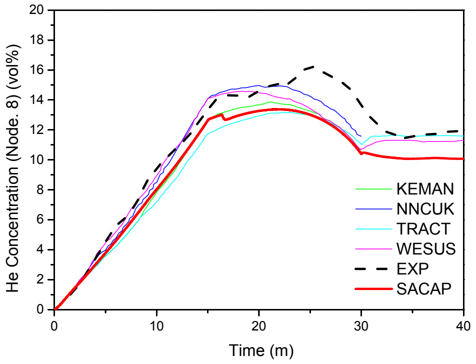

Fig. 2. He concentration of injection node in ISP-35

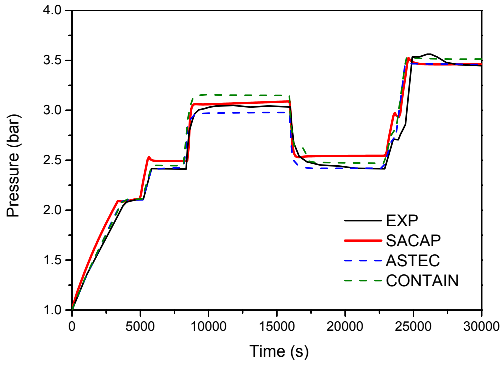

Fig. 3. Experimental and simulated pressure variations in ISP-47

2.2 Steam Explosion Analysis Module

The steam explosion is a strong fuel-coolant interaction that occurs when the molten liquid corium of high temperature contacts with a kind of volatile liquid of low temperature. Before the explosion, two liquids having high temperature difference would form a mixture in the shape of a kind of bubble composed of a fragments of hot liquid covered by the layer of the evaporated gas of the cooler liquid. When the gas layers of bunch of these bubble-like mixture are broken, a rapid heat transfer is followed between two liquids to bring a rapid evaporation and to develop a shock wave which possibly produce a large mechanical impact onto the wall of the surrounding reactor cavity structures.

There are several steam explosion analysis codes developed already such as ESPROSE-m, IDEMO, IFCI, IKEMIX, JASMINE, MATTINA, MC3D, PM-ALPHA, TEXAS-V, TRACER, VAPEX and VESUVIUS.[6] Generally, these codes adopt a kind of mechanistic model concept and some of those can treat the 3-dimensional domain. Most of these codes are dedicated to analysis of the steam explosion and pursuing high accuracy and fine resolution of the solution.

For developing an integral code which can cover the overall NPP regions and combined phenomena, relatively simple and parametric modeling approach is applicable more than the detailed and mechanistic one. Fig. 4 shows the basic concept of the molten corium fragmentation and mixing model based on Moriyama's[7]. The molten corium fragments are generated through the cone-shaped boundary in time-dependent manner. This cone-shaped corium is handled in jet nodes and the fragments detached from the jet are handled in particle nodes. Two node systems are harmonized along the elevation bases and finally the distribution of the fragmented particle can be defined according to the corium jet transition.

The explosion energy is determined by multiplying the energy of the floating fragmented particles at the moment of triggering by a conversion ratio.

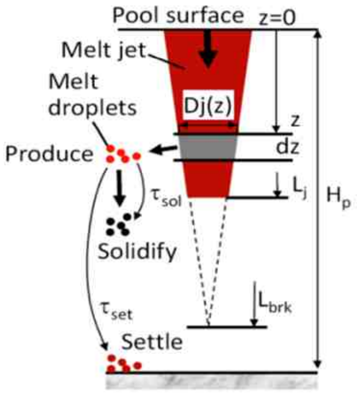

Fig. 4. Modeling concept for corium mixture model

2.3 Direct Containment Heating Analysis Module

DCH(Direct Containment Heating) is a phenomena that occurs when the molten corium is released from the breached reactor vessel with high pressure so as to make the released molten corium be finely fragmented and swept into the upper part of the containment. These corium fragments transfers their heat directly to the containment atmosphere and make the containment pressure abruptly increased.

Several corium disperse empirical correlations available are implemented in SACAP and the user can choose one. The major disperse model is Whally-hewitt's [8] and Levy's[9] and those are implemented in modified forms suitable for time-transient calculation. The corium dispersion calculations have been done for BNL experiments[10] and SNL experiments[11]. Fig. 5 is one of the disperse calculation results for BNL experiment and Fig.6 is a transient calculation results for the SNL IET-5 experiment. From IET-5 experiment, the dispersed mass was 33.12 kg and the amount of the hydrogen production was 319 mole. When Levy's model applied in SACAP calculation, the disperse mass was predicted as 41.1 kg and the hydrogen generation was calculated as 288 mole. Other IET tests simulations also showed similar results with the experimental results.

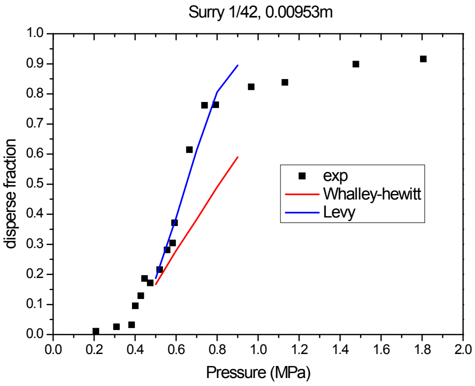

Fig. 5. BNL DCH experiment simulation

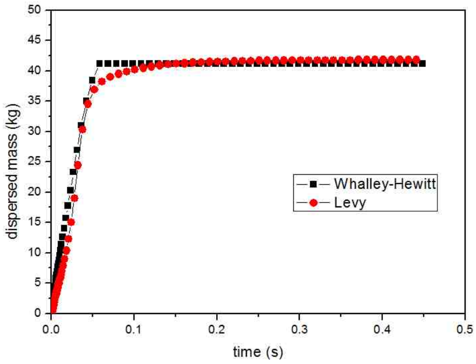

Fig. 6. SNL IET-5 experiment simulation

2.4 Molten Core-Concrete Interaction Analysis Module

When the molten corium released into the reactor cavity, the contacted concrete is decomposed and gases such as steam and carbon dioxide come out being detached from the binding with the concrete materials. The concrete along the corium contacting boundary gets liquefied. The releasing gases make the liquefied concrete mixed with the molten corium so that the mixture layer is formed, the properties of which continuously change as the concrete materials come into the mixture layer.

The metallic materials can be separated from the mixture and form a distinguished layer. There are various modes of heat and mass transfers through the interfaces between the layers and the concrete contacting boundaries. The layer concept diagram is shown in Fig. 7 which mainly presents the energy transfers between layers and at the concrete boundary.

Inside the layers, there are much complicated chemical reactions among the various chemical species of liquids, gases or solids.

In terms of the aerosol generations in the MCCI pool, the chemical reaction would be an important mechanism in that the amount of fission product aerosol release amount can be governed by the chemical reactions. Because that the number of the reactions are very large, a kind of sequential method is not applicable. Thus, chemical equilibrium status is searched so that the Gibbs energy of the reaction system can be minimized. In SACAP, a quasi-steady chemical equilibrium condition can be determined by finding the minimum Gibbs energy state using the steepest decent method and the Lagrange multiplier method. The results of SACAP chemical equilibrium model was compared with the CSNI[12] solutions and the molar amounts of major species were found similar with each other.

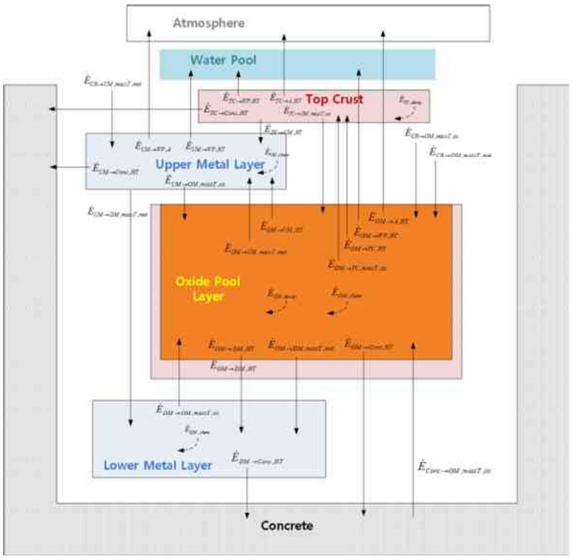

Fig. 7. MCCI layer concept diagram - Energy Transfers

Once the chemical equilibrium state is solved, gaseous species moves upward in the form of bubbles and a part of liquid species can evaporate into the rising bubbles. When these bubbles escape into the upper containment atmosphere, the gaseous species retained in the bubbles would form aerosols by condensation. In SACAP, this kind of bubble dynamics and aerosol generation mechanism is implemented.

Currently, basic equations of the layer configuration, concrete ablations model, the chemical equilibrium model, bubble dynamic and aerosol generation model are systematically combined into SACAP MCCI module and the module is under V&V stage.

3. Summary

In this paper, the overview of the SACAP development status is presented. SACAP is developed so as to be able to analyze, so called, Ex-Vessel severe accident phenomena including thermal-hydraulics, combustible gas burn, direct containment heating, steam explosion and molten core-concrete interaction. Currently, most of the module structures have been established and efforts of V&V are expedited. At the parallel time, SACAP and In-Vessel analysis module named CSPACE are processed for integration through

MPI communication coupling. Development of the integrated severe accident analysis code system will be completed in following one year to make the code revision zero to be released.

ACKNOWLEDGEMENT

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