Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, 2003

Improvement of the Thermal Hydraulic Capability of MAAP4 with Implementation of Pseudo Pressure Effect

Chang Hwan Park, Yong Soo Kim, U. C. Lee, G. C. Park, and K.Y.Suh

Seoul National University
San 56-1 Sillim-Dong, Kwanak-Gu, Seoul, 151-742, Korea

Abstract

The water level decrease in core has directive effect on the following severe accident. This fact is also applied into MAAP4 calculation. MAAP4 is a code for calculation of the severe accident and the thermal hydraulics in MAAP4 plays a role to present the only boundary conditions for severe accident sequence. Thus, the thermal hydraulic models in MAAP4 are relatively simplified and MAAP4 shows some inaccuracies, one of which is about the water level prediction. To check the propriety of water level calculation of MAAP4, an experiment, called THETA, was performed and the results were compared with those of MAAP4. It is found that the decreasing rates of water level in core and downcomer are somehow deviated from the results of the experiment. After examination of the results, it was found that the fundamental weakness of MAAP4 is related to the static head balance between the core and the downcomer. MAAP4 doesn't have momentum equation set so that it cannot consider the effect of the differential pressure between core upper plenum and downcomer region. With this reason, MAAP4 predict wrong result about the distribution of water mass in the core and downcomer. To solve this problem, a correction term, named '*Pseudo Pressure Build-up Term*' was implemented into MAAP4 and the improvement of water level calculation was achieved.

1. Introduction-Water Level Balance Problem of MAAP4

The experiment was performed that is a LOCA experiment with the SNUF facility, which is scaled down to 1/6.4 in length and 1/178 in area from the APR1400. This was simulated with MAAP4 code, which is well-known for good abilities in severe accident calculation, but it has relatively simplified thermohydraulic models. It doesn't have momentum equation and calculate water inventory distribution with very simple physics.

In the experiment, the mixture level of core keeps lower than the collapsed water level in the downcomer region. This phenomenon is due to the pressure build-up in the upper plenum region caused by steam generation in the core. The primary system loop forms flow resistances which make the downcomer pressure lower that that of core upper plenum.

MAAP4 considers only static head balance as the mechanism of water level distribution. MAAP4 takes primary system as one control volume. So there are not defined pressure differences between each system node in MAAP4. Investigating the water level in core and downcomer, MAAP4 shows the higher mixture level at all experiment time. This water level distribution might influence on decision core water level decrease rate. Fig.1 and Fig.2 show the difference between the results of the experiment and MAAP4.

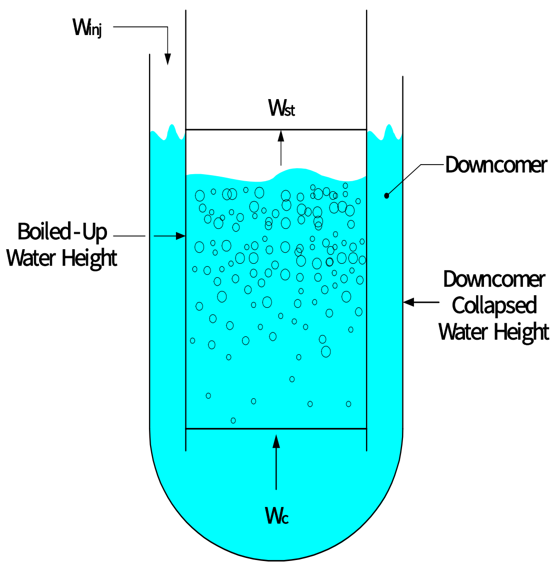

Fig.1 Water level in the experiment

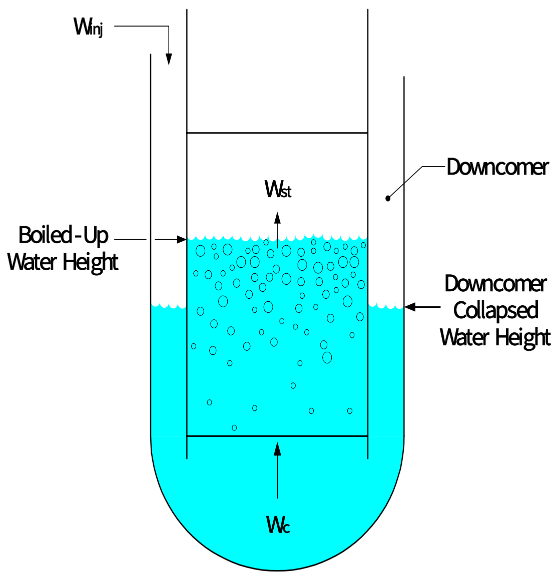

Fig.2 Water level in MAAP4

MAAP4 calculates only gravity driven flows in determination of water level distribution in primary system. Eq.(1) represents core inflow calculation based on static head difference.

$$W_c = C_d A_c \rho_w \sqrt{2g(h_{DC} - h_c)} \qquad (1)$$

With only static head balance, MAAP4 makes downcomer water level higher than that of core in any occasion. But in real situation, in experiment, core mixture level keeps higher than the collapsed water level in downcomer due to the pressure build-up in core upper plenum region.

The parameter, the mixture level in core, has much importance on decision of severe accident processes in MAAP4. The fraction of core uncovery is obtained based on the mixture level in core. So this parameter is important one to be predicted more accurately.

There are several parameters that determine the core mixture level. Those are steam generation rate in core, core void fraction and the balance of water level between core and downcomer. Steam generation rate is calculated simply based on system water enthalpy. And core void fraction is decided by Wallis's drift flux model. There is room for modification of these two parameters. The calculated result of steam generation of MAAP4 is found in the range where it is physically acceptable. With respect to core void fraction, there could be several model sensitivity studies with adjustable drift flux models developed recently.

In this study, the third one, water level balance between core and downcomer is mainly treated. Unrealistic water level balance might induce wrong inflow to core from downcomer. Because MAAP4 considers only gravity effect on water level calculation, the core mixture level keeps higher than the collapsed water level in downcomer. In real situation, there is pressure build-up in the upper plenum of core. So the water level of downcomer is higher than the mixture level of core.

To correct the problem above, MAAP4 was modified with adjusting pseudo pressure build-up in core region. The reason of '*pseudo*' is that the pressure build-up made by modification does not make real pressure difference between core and downcomer. It is only make pressure build-up effect on water level calculation so that the water level distribution should get more realistic. The method and the results are described on the followings.

2. Description of Work

2.1 Implementation of Pseudo Pressure Build-up Term

Because MAAP4 doesn't define the pressure differences between each gas node, there is no way to handle the nodal pressure. Strictly speaking, there is only one pressure node, primary system, in MAAP4. It is very hard to make momentum equation to define nodal pressures and it needs also a code restructuring of vast scope. Thus, to make MAAP4 consider differential pressures in each node is considered out of range.

Instead of that, it was considered that utilizing the gas flows calculated at previous time step would enable us to deduce the pressure drop through the primary system loop. Using the gas flows, we can calculate the pressure drop from core to downcomer, which can be used as core pseudo pressure build-up and pressure build-up term is added to the core static head. Then the core mixture level is pushed down and collapsed water level of downcomer get higher The effect of this pseudo pressure build-up is limited only in water level determination. But modified distribution of primary system water level induces the core inlet flow to be changed. This newly achieved core inlet flow makes the decreasing rate of core mixture level to be changed.

The numerical expression of core pressure build-up is Eq.(2). In this study pump is not considered, so the last term of Eq.(2) is neglected.

$$\Delta P_{pseudo} = P_{in} - P_{out} = \frac{L}{\overline{A}}\frac{dW}{dt} + \left[\left(\frac{\overline{\rho A}}{\rho_{out}A_{out}}\right)^2 - \left(\frac{\overline{\rho A}}{\rho_{in}A_{in}}\right)^2\right]\frac{W^2}{2\overline{\rho A}^2} + f\frac{W^2}{2\overline{\rho A}^2} + \overline{\rho} g(z_{out} - z_{in}) - \overline{\rho} g H_p(W) \quad (2)$$

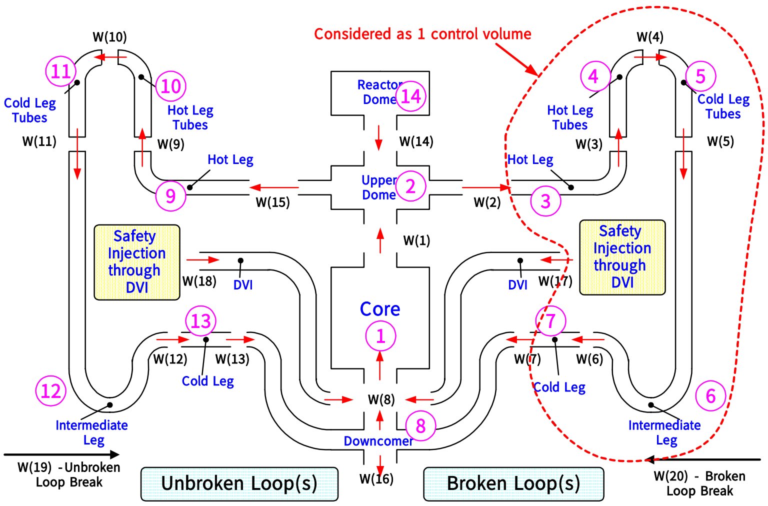

Fig.3. Selection of control volume for calculation of pseudo pressure build-up

To implement Eq.(2) in MAAP4, following numerical simplification is adapted. For the first, the broken loop is chosen as a control volume to calculate the pseudo pressure build-up. The inlet of this control volume is the inlet of gas node 3, and the outlet is that of gas node 7. So gas flows of interest are W_2 and W_7 as shown in Fig.3. The densities, flow areas and gas flows of each node are averaged to be simplified reasonably. And then each terms of Eq.(2) are defined with simplified node parameters.

$$\overline{\rho} = \frac{(\rho_7 + \rho_3)}{2} \quad (3)$$

$$A = \frac{(A_7 + A_3)}{2} \tag{4}$$

$$W = \frac{W_2 + W_7}{2} \tag{5}$$

$$\rho_i = \rho_3 \tag{6}$$

$$\rho_o = \rho_7 \tag{7}$$

Using Eq.(3)~(7), the each term of Eq.(2) can be expressed as followings.

-inertia term

$$\Delta P_{inetia} = \frac{L}{\overline{A}} \frac{dW}{dt} = \frac{(W_2 + W_7)^{n+1} - (W_2 + W_7)^n}{\Delta t} \cdot \frac{L}{(A_3 + A_7)} \tag{8}$$

-acceleration term

$$\begin{aligned} \Delta P_{acceler} &= \left[\left(\frac{\overline{\rho A}}{\rho_o A_o} \right)^2 - \left(\frac{\overline{\rho A}}{\rho_i A_i} \right)^2 \right] \cdot \frac{W^2}{2 \overline{\rho A}^2} \\ &= \frac{1}{32} (\rho_7 + \rho_3)^2 (A_7 + A_3)^2 \left[\frac{1}{(\rho_7 A_7)^2} - \frac{1}{(\rho_3 A_3)^2} \right] \cdot \frac{(W_7 + W_2)^2}{(\rho_7 + \rho_3)(A_7 + A_3)^2} \end{aligned} \tag{9}$$

-viscous term

$$\Delta P_{viscous} = f \frac{W^2}{2 \overline{\rho A}^2} = f \cdot \frac{(W_7 + W_2)^2}{(\rho_7 + \rho_3)(A_7 + A_3)^2} \tag{10}$$

-hydrostatic term

$$\Delta P_{hydro} = \overline{\rho} g (z_o - z_i) \cong g(\rho_7 z_7 - \rho_3 z_3) \tag{11}$$

Finally, the total pressure build-up is to be Eq.(12)

$$\Delta P_{pseudo} = \Delta P_{inertia} + \Delta P_{accler} + \Delta P_{viscous} + \Delta P_{hydra} \tag{12}$$

In the viscous term, the flow resistance factor f has significant effect in determination of total amount of pseudo pressure build-up. To estimate this value, the experimental pressure drop data are utilized, which are divided by the value of $\rho v^2 / 2$.

$$f = \frac{\Delta p}{\rho v^2 / 2} \tag{13}$$

MAAP4 cannot calculate the pressure distribution of the system, so the pressure drop data cannot be estimated except from the experiment. The value of f can be estimated by combination of the data of the experiment and that of MAAP4 calculation. The value of $\rho v^2 / 2$ has range from 2.5 to 7.0 through the whole calculational period and the total loop pressure drop is measured to be 1200 Pa. Then, the value of f gets to be in the range from 171 to 600 (Shown in Table1). Finally, the value of f is determined by the sensitivity study with several f values. This process may have some uncertainties, but this is considered as reasonably possible method because that MAAP4 does not calculate the momentum equation and cannot give the pressure drop data. The value of f used in final calculation is

495.0.

Position of DP measurement	Value of Measured DP (Pa)	Sum of measured DP (Pa)	$\rho v^2/2$ calculated in MAAP4 (kg/m·sec^2)	Factor of Flow Resistance $f=\frac{\Delta p}{\rho v^2/2}$
CL_LDC	115	1199	2.5 ~ 7.0	171.286~599.5
LDC_LP	1			
LP_UP	10			
UP_HL	168			
HL_SGO	850			
SGO_COL	55			
COL_DCH	-			

Table 1. The flow resistance factor *f*

2.2. Calculation of Gas Flow Rate in MAAP4

This part is to show the propriety of the values of the gas flow rates that are calculated in MAAP4. Gas flows are created into and out of the nodes due to sources or sinks of gas in the nodes, imbalances in static head around the system, pressure differences between the primary system and containment and changes in node gas temperature. This can be described by following numerical expression.

$$\dot{P} V_i + \dot{V}_i P = \dot{n}_i RT_i + n_i R \dot{T}_i \qquad i = 1,\ldots N \qquad (14)$$

$$\sum_{flowpaths} K_j W_j |W_j| = \sum_{nodes} g\Delta z_i \rho_i \qquad \text{internal primary system flow loops} \qquad (15)$$

$$\sum_{flowpaths} K_j W_j |W_j| = \sum_{nodes} g\Delta z_i \rho_i + P - P_c \qquad \text{break flow paths and genrealized opening paths} \qquad (16)$$

Eq.(14) is just the time derivative of the equation of state. The terms in Eq.(14) are not those of primary system gas nodes but those of containment compartments. The primary system is considered as one node. In the primary system, pressure differences between each gas node are not calculated. With the result of Eq.(14), primary system can only give boundary conditions to containment compartment not considering inner primary system pressure differences MAAP4 doesn't have momentum equation. However, it can calculate the gas flow rates with quasi-steady momentum equation. Eq.(15) and Eq.(16) represent quasi-steady momentum balances over various combinations of flow junctions. The gas flows in each node are calculated with iterations in matrix solver to get convergence.

In this equation set, dominant parameters are static head differences in the primary system gas nodes and the pressure difference between primary system and containment. The break flow of system is calculated in other subroutine independently and then it is used as a kind of source term of equation set above. The results of these equation set are used in estimation of trace and distribution of gaseous fission products. Though the gas flow distribution given by equation set above can be considered as somehow rough mapping of distribution of flows keeping balances in the system, the results are found that the amount of flow rates is predicted properly.

2.3. The Logic of Implementation of Pseudo Pressure Build-up

The pseudo pressure build-up term is implemented in MAAP4 appropriately as shown in Fig.4.

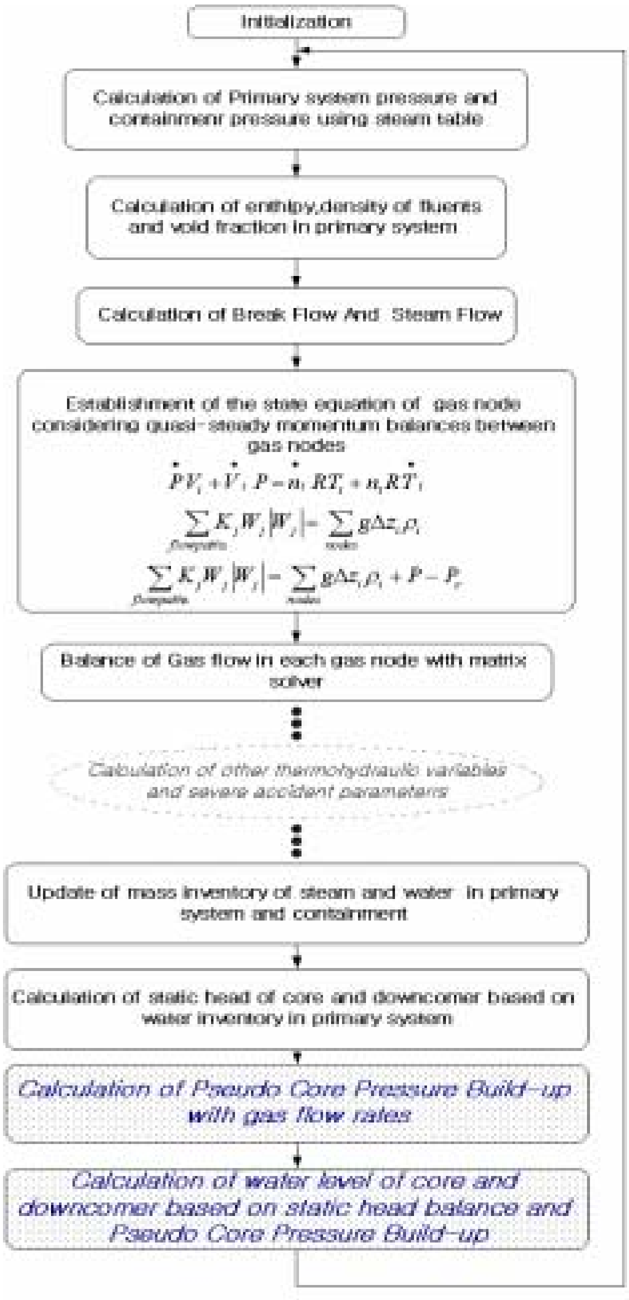

Fig.4. Overall flow chart of implementation of pseudo pressure build-up

3. The Results

3.1 The Results after Implementing the Pseudo Pressure Build-up

With implementation of pseudo pressure build-up, the water level distribution in core and downcomer get more realistic. The water level balance is newly established by additional pressure build-up. And resultant core mixture level is changed to be more similar to that of experiment (Fig.5). The downcomer water level also gets more similar to experimental data (Fig.6). The important thing is that the inclinations of water level data are changed to be more realistic.

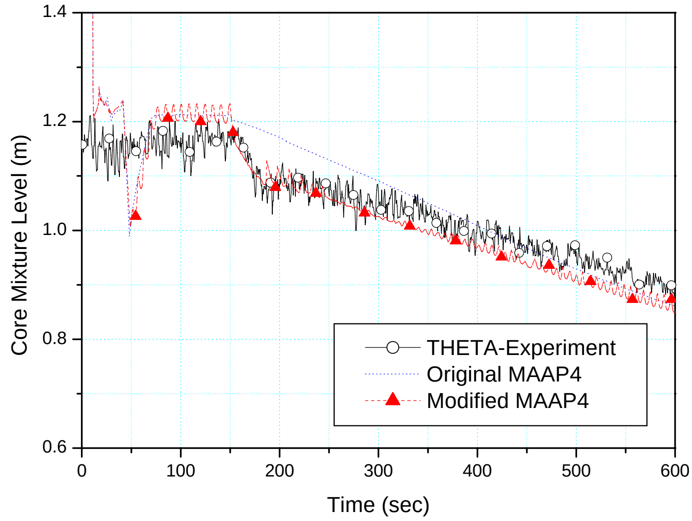

Fig.5. The core mixture level

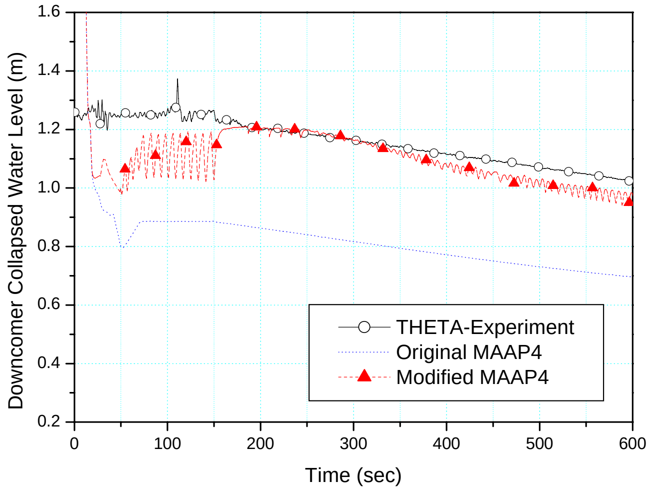

Fig.6. The collapsed water level in downcomer

The results of the temperature of core water and the pressure of primary system are compared with those of experiment. MAAP4 shows the water temperature as nearly same with experiment (Fig.7). However, the pressure of primary system deviates somehow from the experimental result (Fig.8). These data have little difference after implementation of the pseudo pressure build-up term. The analysis of the data of temperature and pressure are not considered as to be in the scope of this study, but only considered to be the fundamental data required to assure the validity of the MAAP4 calculation. MAAP4 calculates one value of primary system pressure, which is the value averaged over the entire system. Thus, the primary system pressure of MAAP4 is not in accord with that of experiment, so the difference is not easy to be analyzed or qualified.

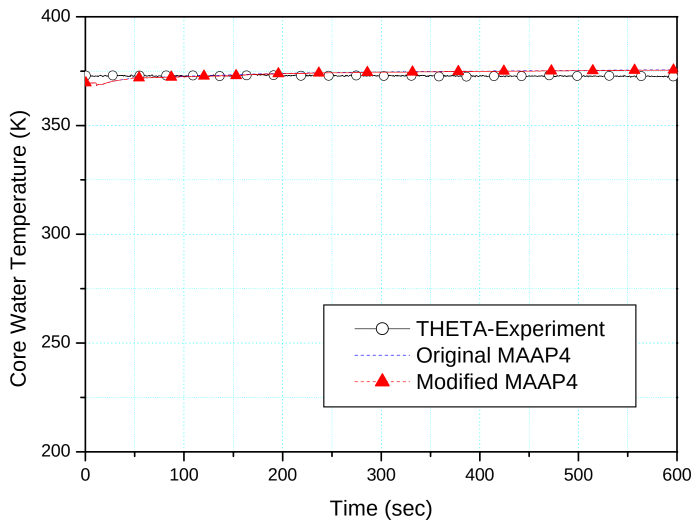

Fig.7. The temperature of core water

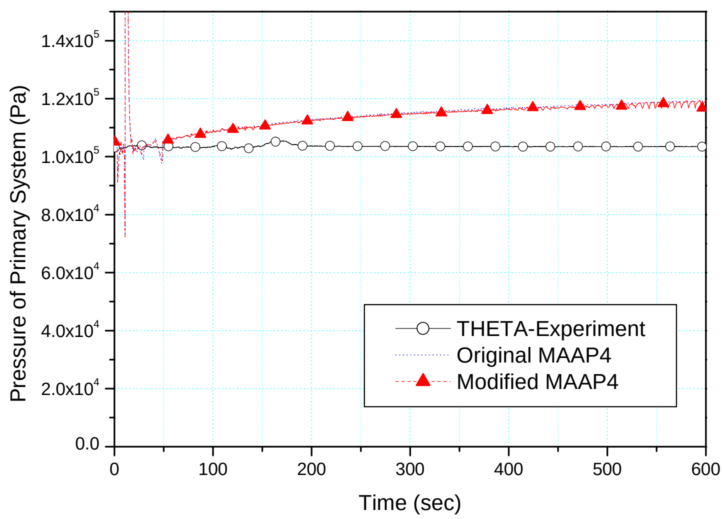

Fig.8. The pressure of the primary system

3.2. Effect of Modified Mixture Level on Severe Accident

The results of implementation of pseudo pressure build-up are shown from Fig.9 to Fig.13. Mixture level decrease rate of core was changed after implementation of core pressure build-up. The decrease rate of mixture level was mitigated after modification, which made effect on core water inventory and water temperature. Because the downcomer water level gets higher than before, the reactor vessel can keep larger amount of water and then system water temperature gets lowered than before. The slowing down of mixture level decrease and the lowered water temperature mitigate following severe accident process. Finally, core melting time is delayed by hundreds of second (Fig.13)

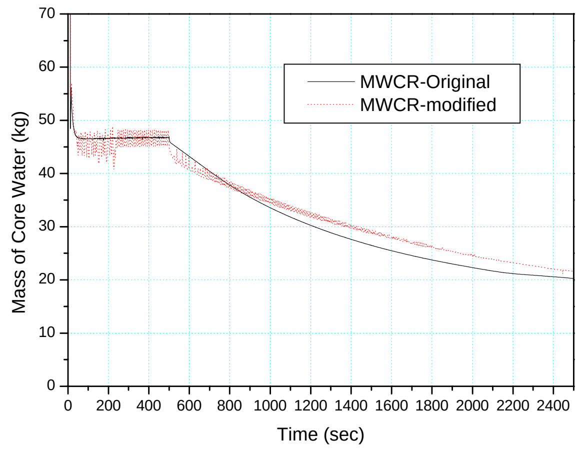

Fig.9. Mass of core water

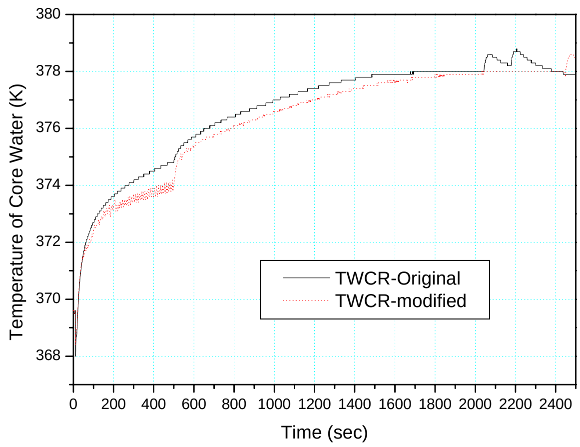

Fig.10. Temperature of core water

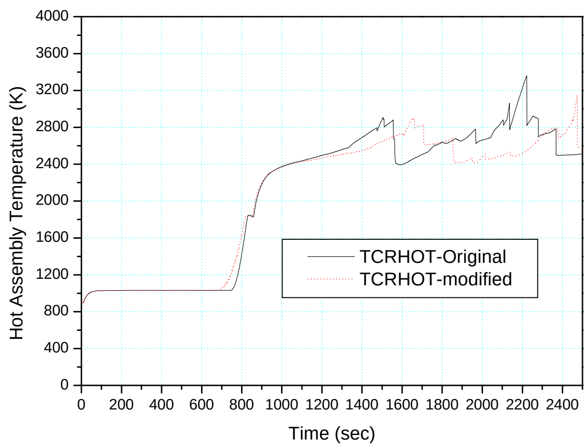

Fig.11. Hot assembly temperature

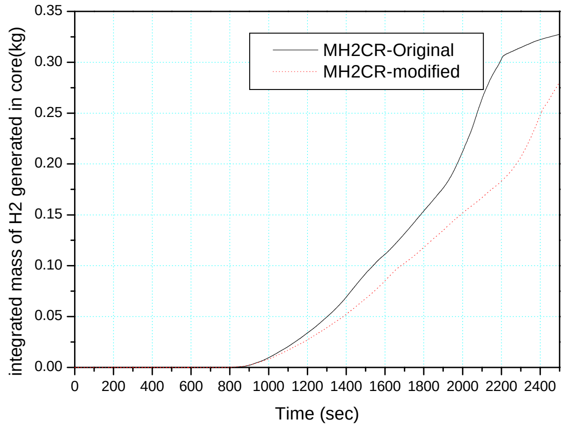

Fig.12. Integrated mass of H_2 generated in core

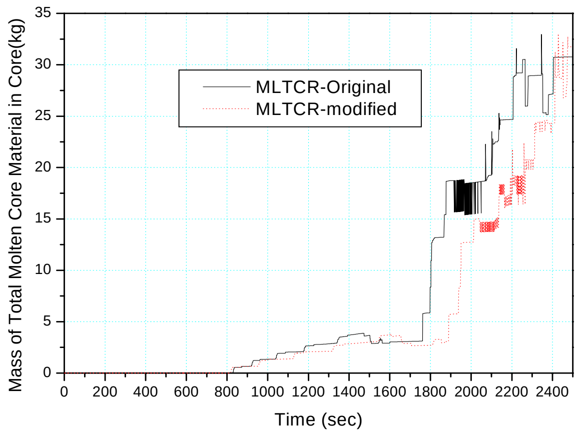

Fig.13. Mass of total molten core material in core

4. Conclusion

The experiment, THETA, was simulated with MAAP4 code and there are found some discrepancy between the experiment and the code. In the experiment, the mixture level of core keeps lower than the collapsed water level in the downcomer region. This phenomenon is due to the pressure build-up in the upper plenum region caused by steam generation in the core.

In MAAP4, the mixture level in core has much importance on decision of severe accident processes in that the fraction of core uncovery is obtained based on the mixture level in core. So this parameter is important one to be predicted more accurately.

There are several parameters that determine the core mixture level. Those are steam generation rate in core, core void fraction and the balance of water level between core and downcomer. In this study, the water level balance between core and downcomer is mainly considered. Because MAAP4 considers only gravity effect on water level calculation, the core mixture level keeps higher than the collapsed water level in downcomer. In real situation, there is pressure build-up in the upper plenum of core. So the water level of downcomer is higher than the mixture level of core.

To correct this problem, MAAP4 was modified with adjusting pseudo pressure build-up in core region. The reason of ‘pseudo’ is that the pressure build-up made by modification does not make real pressure difference between core and downcomer. It is only make pressure build-up effect on water level calculation so that the water level distribution should get more realistic.

Because MAAP4 doesn’t define the pressure differences between each gas node, there is no way to handle the nodal pressure. Strictly speaking, there is only one pressure node, primary system, in MAAP4. However, implementing of pseudo core pressure build-up effect can be taken as a practical method that can induce realistic water level balance.

With utilization of the gas flows calculated ahead and simplification of nodal parameters, the pressure drop through the primary system loop could be calculated. And this result was used pseudo pressure build-up.

As the results, the decrease rate of mixture level was mitigated and that made effect on core water inventory and water temperature. Finally, the severe accident was somehow mitigated.

In this study, it was tried to find the way with which make the thermohydraulic capability of MAAP4 to be enhanced. Although the results of that shows more realistic calculation of core mixture level, there are still several rooms for more accurate modification such as consideration of subcooling effect in calculation of steam generation rate and modification of drift flux model related to core void fraction.

The pseudo pressure build-up term would be an example of many possible ways of modification of MAAP4. With more localized experiment and several model sensitivity studies, the modification of MAAP4 is expected to be more valid and clearer.

NOMENCLATURE

C_d	inertial and frictional resistance	
A_c	core inlet flow	[m^2]
ρ_w	primary system water density	[kg/m^3]
g	gravity acceleration	[m/sec^2]
h_{DC}	collapsed height of downcomer node	[m]
h_c	collapsed height of core node	[m]
ΔP_{pseudo}	pseudo pressure build-up in core region	[Pa]
W	average flow rate of total loop average	[kg/sec]
L	total length of flow path	[m]
P_{in}	inlet pressure	[Pa]
P_{out}	outlet pressure	[Pa]
z_{in}	elevation of inlet loop nozzle	[m]
z_{out}	elevation of outlet loop nozzle	[m]
f	flow resistance	
$\overline{\rho}$	average density of gas	[kg/m^3]
ρ_{in}	density of inlet gas	[kg/m^3]
ρ_{out}	density of outlet gas	[kg/m^3]
H_p	pump head	[m]
$\overline{A}$	average area of total loop	[m^2]
A_{in}	average area of inlet	[m^2]
A_{out}	average area of outlet	[m^2]

ρ_3	density of gas in gas node 3	[kg/m^3]
ρ_7	density of gas in gas node 7	[kg/m^3]
A_3	flow area of gas node 3	[m^2]
A_7	flow area of gas node 7	[m^2]
W_2	gas flow rate of gas in gas node 2	[kg/sec]
W_7	gas flow rate of gas in gas node 7	[kg/sec]
X^{n+1}	value of X in current time step	
X^{n}	value of X in last time step	
$\Delta P_{inertia}$	inertia term of pressure build-up	[Pa]
$\Delta P_{acceler}$	acceleration term of pressure build-up	[Pa]
$\Delta P_{viscous}$	viscous term of pressure build-up	[Pa]
ΔP_{hydro}	hydrostatic term of pressure build-up	[Pa]
P	primary system pressure	[Pa]
V_i	gas volume of node i	[m^3]
$\dot{n}_i$	total rate of change of number of moles in node i	[moles/sec]
$\dot{T}_i$	rate of change of gas temperature in node i	[K/sec]
K_j	frictional loss coefficient of junction j	
R	ideal gas constant	
Δz_i	height of node i	[m]
ρ_i	density of gas in node i	[kg/m^3]
P_c	containment pressure	[Pa]

REFERENCES

1. R. E. Henry, et al., “MAAP4 User’s Manual,” Fauske & Associates, Inc., Burr Ridge, IL, USA, 1994.

2. E.E. Lewis, “Nuclear Power Reactor Safety”,John Wiley & Sons, 1977

3. Neil E. Todreas , Mujid S. Kazimi, “Nuclear Systems I, Thermal Hydraulic Fundamentals”, Hemisphere Publishing coporation,1990.

4. John C. Tannehill, et al, “Computational Fluid Mechanics and Heat Transfer” 2nd edition, Taylor & Francis, 1997.