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⟨Technical Note⟩

Post Test Analysis to Natural Circulation Experiment on the BETHSY Facility Using the MARS 1.4 Code

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Abstract

The present study is to assess the applicability of the best-estimate thermal-hydraulic code, MARS 1.4, for the analysis of thermal-hydraulic behavior in PWRs during natural circulation conditions. The code simulates a natural circulation test, BETHSY test 4.1a, which was conducted on the integral test facility of BETHSY. The test represented the cooling states of the primary cooling system under single-phase natural circulation, two-phase natural circulation and the reflux condensation mode with conditions corresponding to the residual power, 2 % of the rated core power value and 6.8 MPa at the secondary system. Based on MARS 1.4 calculations, the major thermal-hydraulic behaviors during natural circulation are evaluated and the differences between the experimental data and calculated results are identified. The calculated results show generally good behavior with regard to the experimental results; the region of single-phase natural circulation is 100~92 % of the initial mass inventory, two-phase natural circulation is 84~63 %, and the reflux condensation mode occurred below 58 %. U-tubes empty and the core uncovery are obtained at 39 % and 34 % of the initial mass inventory, respectively.

Key Words : natural circulation, reflux condensation, MARS code, BETHSY experiment, flow oscillation, termination of two-phase natural circulation.

1. Introduction

The safety of current pressurized water reactors (PWRs) mainly depends on the passive engineered safety features to enhance their reliability. Many concepts have been proposed for the next generation PWRs in which passive safety functions are pursued. Natural circulation is an important passive heat removal mechanism in both existing and next generation PWRs. Also, natural circulation is a principal heat removal mechanism following a loss of coolant accident (LOCA) in a loop type PWR [1, 2] as well as in a system-integrated modular advanced reactor (SMART) [3]. In the course of SMART development, the natural circulation has been extensively studied at the

Korea Atomic Energy Research Institute because of its important role. The SMART is mitigated the consequence of design basis events by the natural circulation mechanism [3]. Also, Samoilov et al. [4] investigated a passive RHR (Residual Heat Removal) system for the integral nuclear power reactor with natural coolant circulation. The code capability to predict the physical phenomena and the system behavior during the natural circulation need to be studied extensively because of their important nature in the engineering field. The objective of this study is to assess and validate the code' s capability to predict accurately important phenomena during the natural circulation test, which was conducted on the integral test facility and to find the system behavior associated with natural circulation. Also, this study may contribute to actual applications for plant safety evaluations and descriptions of the physical phenomena for various primary mass inventories under natural circulation conditions.

There are three kinds of natural circulation modes as follows: (1) a single-phase liquid flow, in which liquid is a sub-cooled state [5], (2) a two-phase flow, in which voids generated by the heat addition in the core are circulated and condensed [6], and (3) reflux condensation, in which single-phase steam is condensed in the steam generator and returned to the core [7]. Zvirin et al. [5] and Duffey and Sursock [2] performed the theoretical and experimental study of a natural circulation. The analysis was based on a one-dimensional model in which the continuity, momentum and energy equation were given and solved. Duffey' s model covered all possible heat transfer modes of loop natural circulation and the model has been compared to the available test and plant data. The important parameter governing heat removal for the first two modes is a volume averaged loop mass flow and the loop mass flow is nearly zero in the third mode. Eckhard Krepper and Horst-Michael Prasser [8] performed the pre- and post-test calculation to determine the thermal-hydraulic events for the VVER integral test facility. Under special conditions, periodic oscillations of mass flow and pressure difference occurred. Those were caused by feedback mechanisms among mass flow, heat transfer, steam generation and loop pressure difference. The buoyancy force due to heating in the core and cooling in the steam generator created two-phase natural circulation. That may have had a significantly enhanced heat transfer capability by allowing boiling in the heating section. Son et al. [9] assessed the applicability of the RELAP5/MOD3.2 and CATHARE2 V1.3U codes to analyze reflux cooling behaviors in the u-tubes of PWRs. Tasaka [10] investigated the effect of steam generator secondary inventory on the reflux condensation and No et al. [11] assessed and improved the reflux condensation model when non-condensable gas was present under given conditions.

2. Description of Test Facility and Experimental Results

The BETHSY facility is a full height, 1/100 volume scale and 3-loop integral test facility in France, and is capable of conducting tests relevant to a wide range of LOCA and non-LOCA transients. The reference nuclear power plant is a three loop, 2775 MW thermal FRAMATOME PWR. The maximum operating pressure of the primary and secondary systems are 17.2 MPa and 8 MPa, respectively. Fig. 1 shows a schematic diagram of the BETHSY facility, which consists of a reactor vessel, three primary coolant loops and secondary systems. Each primary loop includes a hot leg, a steam generator, a crossover leg, a reactor coolant pump and a cold leg. A more detailed description of the facility can be found in reference [12].

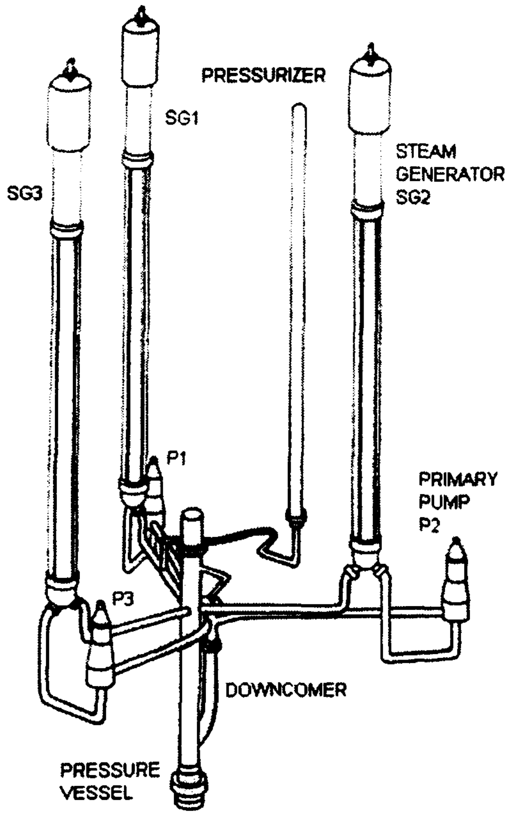

Fig. 1. Schematic Diagram of BETHSY Facility

In BETHSY test 4.1a [13], the primary cooling system was initially in a pressurized single-phase natural circulation state with 573 K in the core outlet and 557 K in the secondary side of the steam generator with three steam generators available. The core power was kept at a constant value of 573 kW, which corresponded to 2 % of the nominal power, for the whole transient and a trace heating of 100 kW was supplied to compensate heat losses for the primary and secondary cooling systems. After the initial condition was established, the test was performed by draining the mass inventory from the bottom of the vessel. Each stage was stabilized for a sufficient period to extract reliable data and the test was terminated at 38400 s due to a rapid increase of the heated rod temperature. The overall purpose of BETHSY test 4.1a was to study the behavior of the primary cooling system in single-phase natural circulation, two-phase natural circulation and the reflux condenser mode.

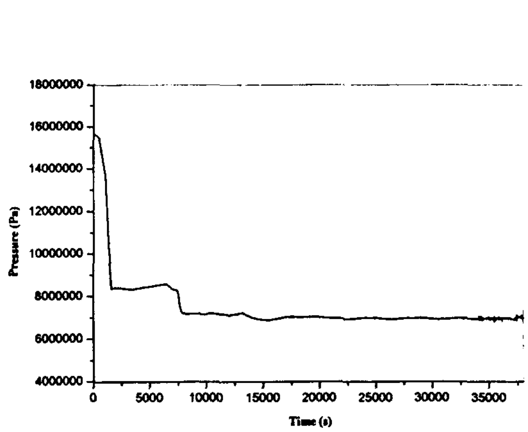

Fig. 2. Measured Upper Plenum Pressure for Various Circulation Modes

After the initial conditions were established at normal pressure, a single-phase liquid natural circulation continued as long as the vapor remained in the top of the pressure vessel. The primary pressure dropped to the saturation pressure corresponding to the liquid temperature in the upper plenum as shown in Fig. 2. As the liquid level in the upper plenum reached the hot leg, the steam entered the steam generator u-tubes through the hot legs, which initiated two-phase natural circulation. The primary mass flow increased its maximum value at 83 % of the initial mass inventory and the peak flow appeared at the maximum value of the pressure difference between the hot and cold legs. Figs. 3 and 4 showed the mass flow in the downcomer and pressure difference between the cold and hot legs, respectively. With the inversion of the pressure difference at the loop boundaries, the upper head to downcomer bypass flow was established and the void appeared in the cold legs. The primary system became unstable state in 63 % ~ 58 % of

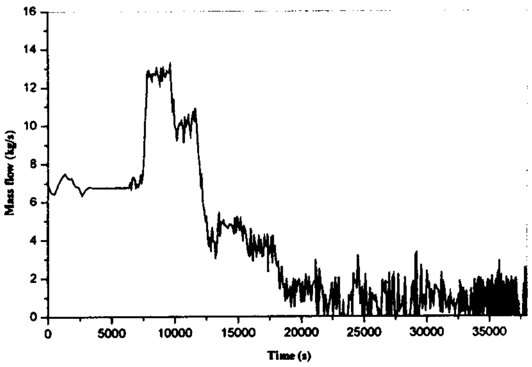

Fig. 3. Measured Mass Flow in the Downcomer for Various Circulation Modes

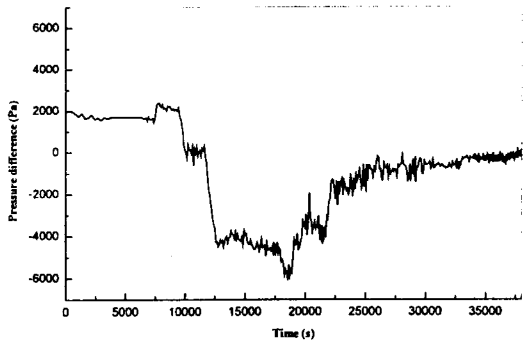

Fig. 4. Measured Pressure Difference Between Cold and Hot Legs for Various Circulation Modes

the initial mass inventory. As the primary mass inventory extracted further, the mass inventory was too low to continue the two-phase natural circulation in the loops. Then the primary loops became the reflux condenser mode. After this transition had been made, a stable reflux condenser mode was established. The liquid was confined in the crossover legs, where the water level in the down-flow part balanced with that in the up-flow part and the water level in the core balanced with that in the downcomer. The core uncovery was occurred by additional drain of the mass inventory and the heated rod temperature reached 870 K. Then the test was terminated to preserve the heated rod.

3. Analysis Method

BETHSY test 4.1a is simulated by MARS 1.4 code [14], which is a modified version improving the deficiency of a multi-dimensional thermal-hydraulic system analysis code, MARS 1.3.1 [15]. The MARS code has been developed by consolidating and restructuring the RELAP5/MOD3.2.1.2 [16] and COBRA-TF [17] codes. Its purpose is adopted to take advantages of the versatile feature of RELAP5/MOD3.2.1.2 and the realistic three-dimensional hydrodynamic module of COBRA-TF. Fig. 5 shows the nodalization of the MARS 1.4 code used for the test facility modeling. The core in the reactor vessel is modeled using 9 volumes. Each loop is modeled using 7, 28, 13 and 6 volumes for the hot leg, steam generator primary, crossover leg and cold leg, respectively. A pressurizer and surge line are not modeled since the surge line is isolated from the beginning of the test. The reactor coolant pump is modeled using a branch component and the pressure drop is adjusted at the reactor coolant pump by the artificial increasing of a form loss coefficient. The upper head to downcomer bypass line is represented by 3 volumes and the minimum cross-section area in the bypass line is modeled by the junction area as finely as possible in order to calculate the bypass flow precisely. The secondary side of the steam generators consists of a cylindrical shell, downcomer, and steam dome. Both the heated rods in the reactor and the steam generator u-tubes are modeled by means of heat structures with or without heat sources, respectively.

To simulate the natural circulation test, the

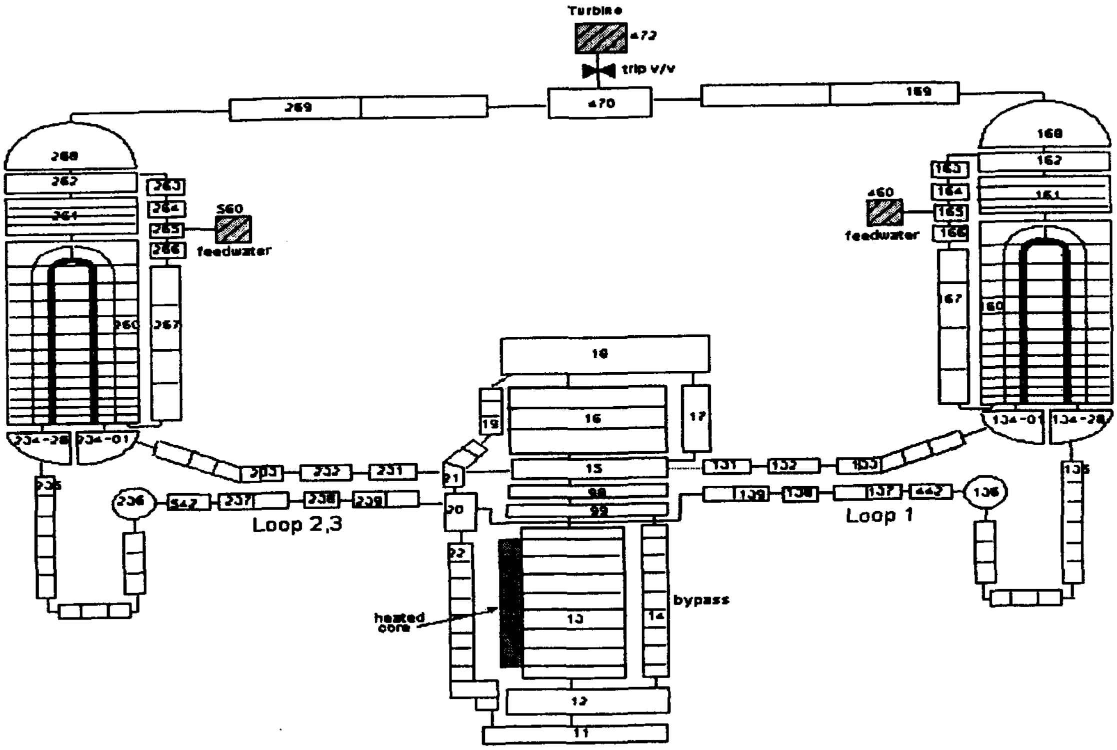

Fig. 5. MARS 1.4 Nodalization for Simulation of BETHSY Facility

Table 1. MARS 1.4 initial Conditions for BETHSY test 4.1a

Parameters	Experiment	Calculation
Power, kW	573±30	573*
Primary system		
Upper plenum pressure, MPa	15.55±0.09	15.58
Core inlet temperature, K	557±4	558
Core outlet temperature, K	573±4	574
Pump speed, rpm	0.0±12	0.0
Loop mass flow, kg/s	2.16-2.29	2.26
Primary coolant mass, kg	1848±28	1827
Secondary system		
SG pressure, Mpa	6.9±0.09, 6.8±0.09, 6.8±0.09	6.80, 6.80, 6.80
SG water level, m	13.6	13.7, 13.7, 13.7
Feedwater temperature, K	389±3, 390±3, 389±3	389, 389, 389*
Steam temperature, K	558±4, 558±4, 558±4	557, 557, 557
Trace heating power, kW	98.5	98.5*

*is input value

system conditions should be determined accurately, which is provided as the initial conditions for the transient calculation. The primary cooling system maintains a single-phase liquid natural circulation condition with the initial pressure of 15.58 MPa with the core power keeping a constant value of 573 kW. The primary cooling system is completely filled with liquid and the liquid temperature at the core inlet and outlet is 558 K and 574 K, respectively. The secondary sides of the steam generators maintain a water level of normal operation with a pressure and steam temperature of 6.8 MPa and 557 K. The feedwater flow with 389 K is controlled to maintain a constant water level for a whole transient. The initial steady state conditions obtained are compared with the measurement data in Table 1. The calculated results are in good agreement with the experimental observations within the measurement errors.

4. Results and Discussion

The system characteristics have been determined by the reactor vessel mass inventory. The calculated results and experimental data are compared in the figures. The major operation map observed for the BETHSY test 4.1a is shown in Fig. 6, which is a primary mass inventory without the surge line and the pressurizer mass inventory for the given power and secondary condition. Simulated time 0~6820 s (2 stages), 7920~21600 s (4 stages) and 22300~38000 s (5 stages) correspond to the single-phase natural circulation, two-natural circulation and the reflux condensation mode, respectively.

4.1. Single-Phase Liquid Natural Circulation Mode

The natural circulation essentially relates to the

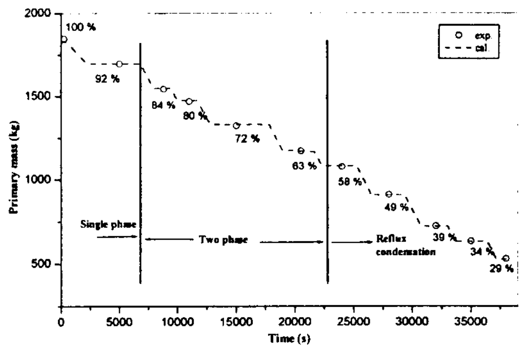

Fig. 6. Primary System Mass Inventory

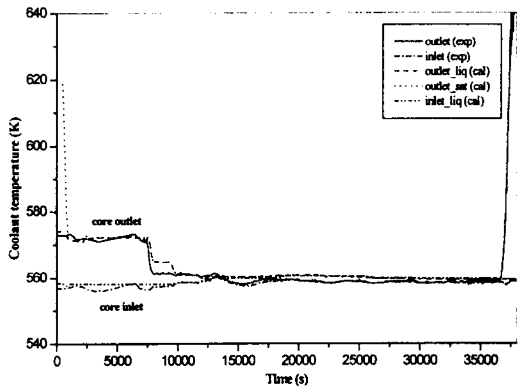

Fig. 7. Fluid Temperature in the Inlet and Outlet of the Core

pressure difference along the primary cooling system. The pressure difference is mainly due to a gravity and friction loss and it represents the coolant distribution in the primary cooling system. As the primary mass inventory is drained from the bottom of the reactor vessel, the primary pressure drops to the value of the saturation pressure corresponding to the liquid temperature in the upper plenum. Fig. 7 shows the temperature distribution in the core inlet and outlet. The liquid temperature remains a constant value at the core inlet; on the other hand, that of the outlet changes to saturation temperature from the sub-cooled

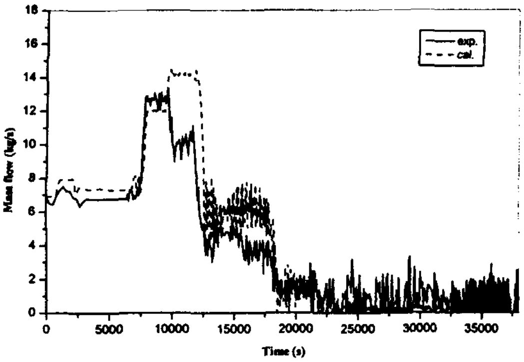

Fig. 8. Mass Flow in the Downcomer

state as the mass inventory is drained from the bottom of the reactor vessel. Fig. 8 shows the variation of the mass flow in the downcomer. The experimental and simulated flow rates have nearly the same value during the single-phase natural circulation. The mass flow depends on the core power, the elevation difference, and loss coefficient for single-phase flow as in the following equation:

$$W_{1\phi} = f(P_o, \Delta L, k_l, A, \rho_l)$$

where P_o, ΔL, k_l, A, ρ_l denote the core power, the elevation difference between the thermal centers of the heat sink and source, the sum of the single-phase frictional and form losses along the loop, the flow area in the leg, and the liquid density, respectively. 6.78 kg/s of the calculated mass flow is in agreement with 6.61 kg/s of the experimental result and 6.87 kg/s of the analytical result, where the measured flow has a maximum deviation from this value of 4 %. Here, the analytical result is calculated by a balance between the gravity and friction terms of pressure differences along the primary cooling system [2].

The density distribution in the steam generator u-tubes is an important parameter to represent the single-phase natural circulation since it relates to temperature distribution and mass flow to remove the generated energy in the core. When the frictional pressure drop in the up-flow and down-flow sides of the u-tubes is nearly the same value, the pressure difference between the u-tube outlet and inlet, DPsg, can be represented as follows:

$$DP_{sg} = (\rho_{ave2} - \rho_{ave1}) g \Delta z - k\rho_{ave} v^2 / 2$$

where Δz is the average height of the u-tube, and subscript 1 and 2 denote up-flow and down-flow sides, respectively. In this experiment, $DP_{sg} \approx 0$, the Reynolds number in the cold leg is around 2.5×10^5, the friction coefficient is 26 [13], and Δz is 9.84 m [12]. Then the pressure loss term is calculated by the equation below:

$$k\rho_{ave} v^2 / 2 = 700\ Pa \quad and \quad (\rho_{ave2} - \rho_{ave1}) = 7.25\ kg/m^3$$

from the point of view of the steam generator gravitational head, the equivalent length (L_{sg}) in the sense of the single-phase natural circulation is :

$$L_{sg} = \frac{(\rho_{ave2} - \rho_{ave1})}{(\rho_{sg,out} - \rho_{sg,in})} \Delta z$$

The calculated L_{sg} is 2.5 m and the experimental L_{sg} is 2.2 m. From those values, MARS 1.4 reasonably predicts temperature distribution in the u-tubes for the liquid single-phase natural circulation.

4.2. Two-Phase Natural Circulation Mode

The range of inventory investigated is 83~63 % of its initial value for two-phase natural circulation. Two-phase natural circulation is established when the two-phase flow exists in the circulation loop. As steam enters the steam generator u-tubes through the hot leg, a transition to two-phase natural circulation occurs when the primary mass

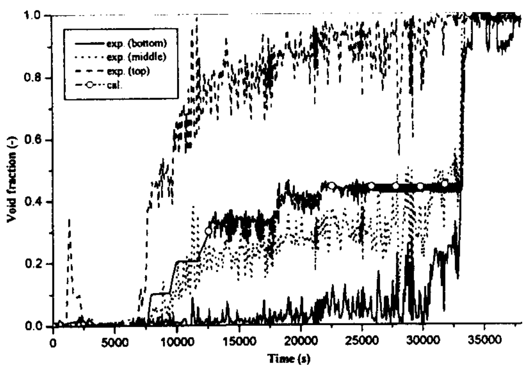

Fig. 9 Void Fraction in the Hot Leg 1

inventory is less than 84 % of the initial inventory in the experiment. Fig. 9 shows the void fraction in hot leg 1. The void distribution in hot legs 2 and 3 is the same value as that in hot leg 1 because the system indicates identical behavior for the three loops during the investigated period. The legend exp.(bottom), exp.(middle) and exp.(top) denote the bottom, center, and top positions of the cross-section, respectively. The test measured the void fraction at 3 positions in order to find the void distribution at one location. The calculated results agree with the experimental data in the middle position of the hot leg. From this result, the void fraction, which is measured at the middle position, has nearly the same value as the volume averaged void fraction by the code. The transition from single-phase to two-phase natural circulation is calculated at the right mass inventory by the code.

Start-up of the two-phase natural circulation mode is accompanied by an increase in the mass flow which reaches a maximum value at ~84 % of the initial mass inventory in the experiment as shown in Fig. 8. The peak flow is ascribed to the initial increase in the driving force by the void formation in the core. The experimental results agree reasonably well with the other experimental data [2]. Other experimental data showed the maximum two-phase natural circulation flow distributed 90~75 % of the system mass inventory, which depended on the reactor power and secondary (or heat exchange) conditions. A temporary reduction of the mass flow in the core inlet flow increases enthalpy, which in turn reduces the average density. A small disturbance of the mass flow caused by a density change results in a small disturbance of the outlet enthalpy, however, that results in relatively large fluctuations of the void fraction at the core outlet. This influences the pressure difference over the core section. The opposite mechanism occurs in the steam generator u-tubes. These affect the pressure difference and heat transfer behavior in the primary system and result in flow oscillations along with multiple regenerative feedback under two-phase natural circulation [8]. Since a flow oscillation can affect system integrity, it is necessary to study the control or elimination of flow oscillation [18]. The calculated mass flow shows a different behavior from the experimental data at 80 % of the initial mass inventory as shown in Fig. 8. The calculated peak flow is 14.1 kg/s at 80 % of the initial mass, while the experimental value is 12.8 kg/s at 84 %. The code does not appropriately predict the mass inventory in which the peak flow occurs. This is caused by the over-prediction of the liquid distribution in the u-tubes at 80 % of the initial mass inventory.

Figs. 10 and 11 show the pressure difference between the outlet and inlet sides of the u-tubes and that of the active core, respectively. The pressure difference between the heat source and heat sink is a main cause of creating the driving force for two-phase natural circulation. The calculated pressure difference in the core is in good agreement with the experimental data for the whole two-phase natural circulation range. At 80 % of the initial mass inventory, the liquid distribution in the down-flow side of the steam

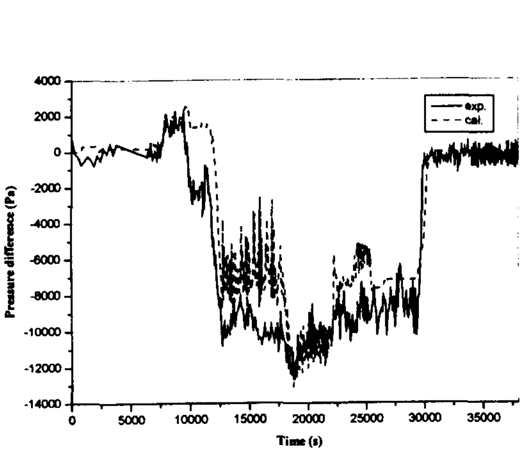

Fig. 10. Pressure Difference Between the Outlet and Inlet Sides in the Steam Generator u-tubes

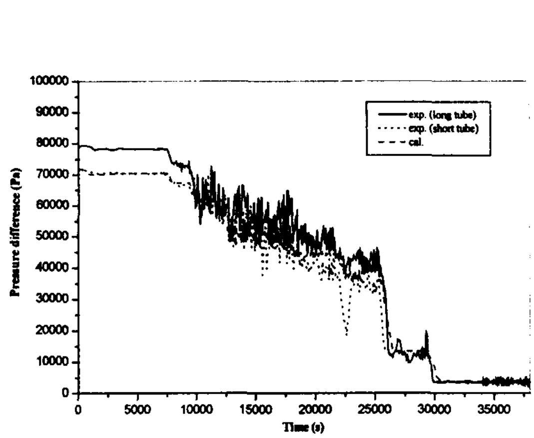

Fig. 12. Pressure Difference in the Up-flow Side of the Steam Generator U-tubes

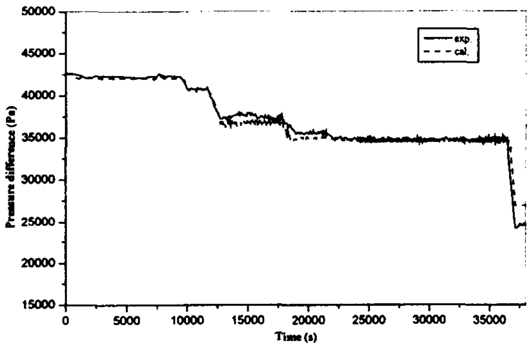

Fig. 11. Pressure Difference in the Active Core

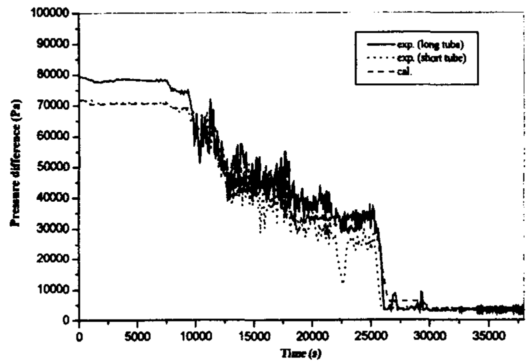

Fig. 13. Pressure Difference in the Down-flow Side of the Steam Generator U-tubes

generator u-tubes is slightly higher than that of the up-flow side in the calculation. However, the liquid distribution of the down-flow side is clearly lower than that of the up-flow side in the experiment as shown in Fig. 10; i.e. in the experimental data, larger voids are located in the upper part of the down-flow side. The differential pressure of the down-flow side is relatively over-predicted at 80 % of the initial mass inventory by the MARS code, though the overall pressure differences at the u-tubes agree well with the experimental data as shown in Figs. 12 and 13. Captions exp. (long tube) and exp. (short tube) denote the differential pressure at the longest and shortest u-tubes in the BETHSY facility, respectively. Though the code predicts well the overall pressure difference in the u-tubes, it has some difference for the relative distribution between the up-flow and down-flow sides. Figs. 14 and 15 show the pressure difference at the up-flow and down-flow sides of the u-tubes for the experiment and calculation, respectively. The pressure difference between up-flow and down-flow sides of experimental data is nearly the same value as that of the calculated result at 84 %;

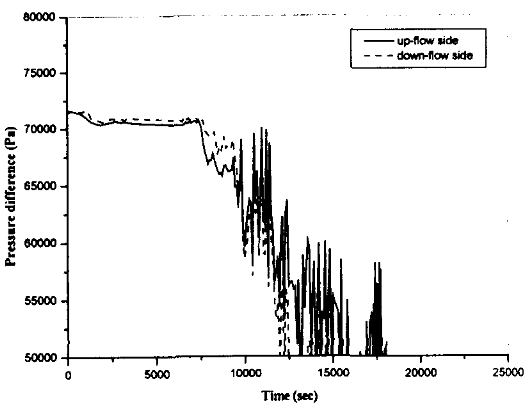

Fig. 14. Pressure Difference in the Steam Generator U-tubes (experiment)

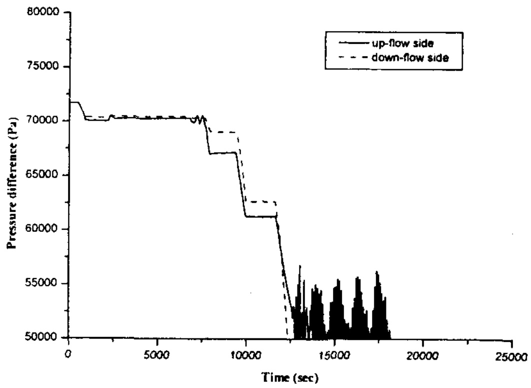

Fig. 15. Pressure Difference in the Steam Generator U-tubes (calculation)

however, it represents a different behavior at 80 %. The code predicts the existence of a larger amount of liquid in the down-flow side than in the experimental data. This may be caused by various factors such as interfacial drag, condensation, two-phase hydraulic friction loss, etc. Sensitivity studies will be discussed in section 4.4. The flow oscillations increase in the lower mass inventory since the vapor flow is not enough for a good liquid circulation. The mass flow decreases continuously with a reduction in the mass inventory and unstable conditions are established in the primary cooling system when the mass inventory is less than 63 % of its initial value. The mass flow at this mass inventory is too low for two-phase natural circulation and too high for reflux condensation. As the mass inventory decreases further, the flow in the primary cooling system develops to a reflux condensation mode.

4.3. Reflux Condensation Mode

Transition to the reflux condensation condition occurs when the primary mass inventory is less than 58 % of the initial mass inventory as the liquid returns to the core through the hot legs. The

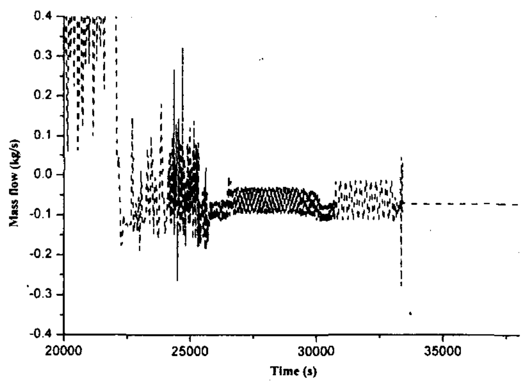

Fig. 16. Calculated Mass Flow in the Hot Leg 1 During the Reflux Condenser Mode

reflux condensation mode is defined as the liquid flow at the inlet of steam generator being on the average negative value. Once the transition from the two-phase natural circulation to the reflux condensation has been made, a stable reflux condenser mode is established when the mass inventory is less than 34 % of its initial mass inventory. Fig. 16 shows the calculated liquid flow in hot leg 1. In the calculation, the liquid mass flow has a slightly negative value with large fluctuations at 58 % of the initial mass inventory. The negative value of the average liquid flow indicates that

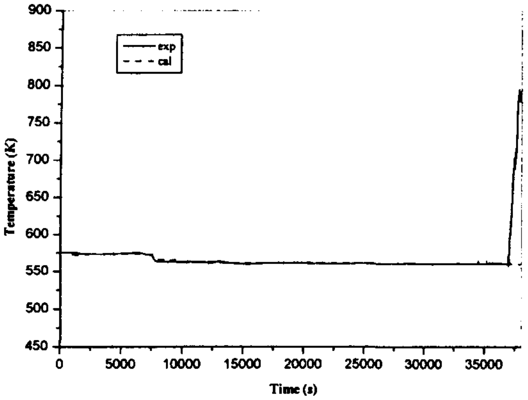

Fig. 17. Peak Temperature on the Heated Rod

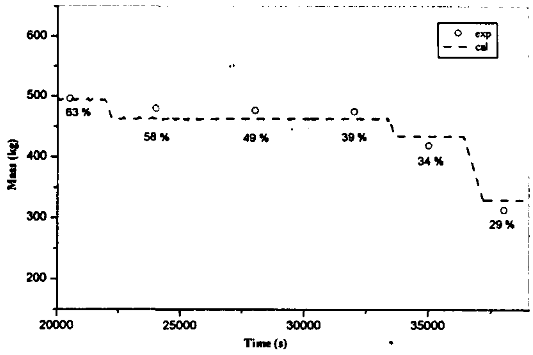

Fig. 18 Mass Inventory Only in the Reactor Vessel

reflux condensation occurs in the steam generator u-tubes. The liquid flow maintains a uniform value after the voids are nearly filled in the hot leg when the mass inventory reaches 34 % of its initial value. The calculated results agree with the experimental data in the center position, as shown in Fig. 9. From this result, we can confirm again that the void fraction measured in the center position has nearly the same value as the volume averaged void fraction by the code. The returned mass flow by reflux condensation is about 0.07 kg/s for each loop in the stable condition, which corresponds to 3 % of the initial loop mass flow. Complete draining in both sides of the u-tubes is observed in the calculation as well as in the experiment at 39 % of the initial value in Figs. 12 and 13. The code predicts well the empty timing of the liquid in the steam generator u-tubes. For a stable reflux condensation mode, the liquid level in the downcomer balances with that in the core, and the liquid confined in the crossover leg where the liquid level in the down flow side balances with that in the up-flow side.

In the experiment, some additional draining of the mass inventory results in core uncovery at 29 % of the initial mass inventory. The clad temperature on the heated rod rapidly increases by about 820 K and the pressure difference between the bottom and top in the active core reduces abruptly as shown in Fig. 11. Fig. 17 shows the temperature distribution of the heated rod at 2.8 m from the bottom of the active core. The timing of the core uncovery is appropriately predicted by the MARS code; however, the cladding temperature does not increase due to over prediction of the liquid distribution in the core as shown Fig. 11. Fig. 18 shows the mass inventory only in the vessel. The mass inventory in the vessel is slightly over-predicted in the final two stages though the difference between the experimental data and calculated results is kept within the bounds of the measurement error range. From this result, we can find that the clad temperature is very sensitive to the mass inventory in the reactor vessel. The effect of a small difference for the mass inventory will be discussed in section 4.4.

4.4. Sensitivity Study for Various Parameters

A sensitivity study is performed to find the effect of the interfacial drag force and the condensation

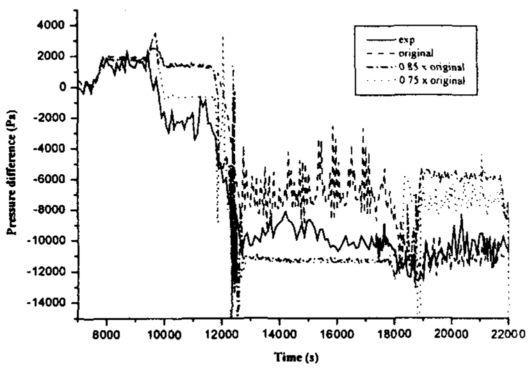

Fig. 19. Pressure Difference Between the Outlet and Inlet Sides in the Steam Generator U-tubes for the Two-phase Naturlation

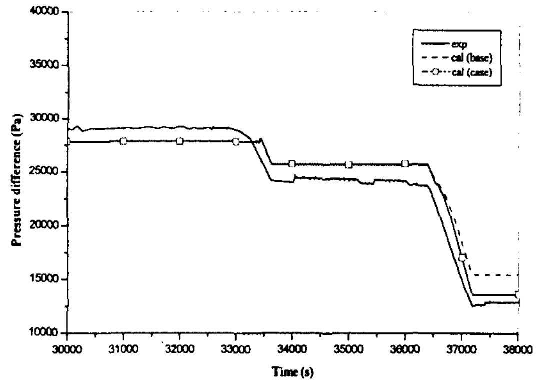

Fig. 21. Pressure Difference in the Active Core for the Reflux Condenser Mode

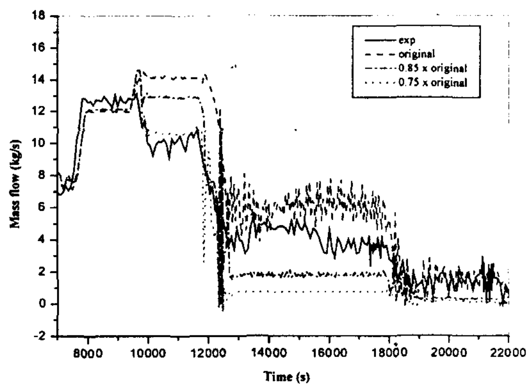

Fig. 20. Mass Flow in the Downcomer for the Two-phase Naturlation

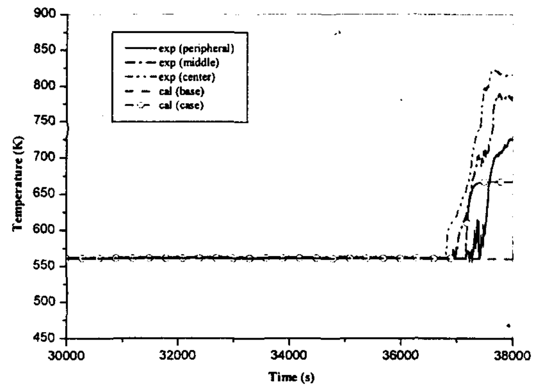

Fig. 22. Peak Temperature on the Heated Rod During the Reflux Condenser Mode

for the pressure difference under the two-phase natural circulation and to find the effect of the system mass inventory for the increase of the clad temperature. The effect of the interfacial drag is investigated in order to predict a better liquid distribution in the u-tubes during the two-phase natural circulation. Figs. 19 and 20 show the pressure difference between the outlet and inlet sides of the u-tubes, and downcomer mass flow by reducing the interfacial drag force. Captions '0.85 x original' and '0.75 x original' denote the reduced interfacial drag force intentionally by 85 % and 75 % of the original value, respectively. The reduced interfacial drag force improves the liquid distribution in the u-tubes and the downcomer mass flow during the first half of the two-phase natural circulation period. However, it does not predict them well for the second half period. The reduced interfacial model can reduce the liquid amount, which is entrained to the down-flow side in the u-tube by the steam velocity. From this result, it is found that the liquid distribution and the mass flow are highly sensitive to the interfacial drag force. The condensation effect is small in the BETHSY test 4.1a during the two-phase natural circulation because the temperature difference between the primary coolant and u-tube wall is very small.

To find the effect of the mass inventory for the clad temperature, the mass inventory is drained additionally in the bottom of the vessel by 20 kg at the final stage. In this case, the calculated mass inventory is still kept within the bounds of the measurement error range for the experimental data. Figs. 21 and 22 show the pressure difference in the active core and the clad temperature on the heated rod, respectively. The differential pressure and the clad temperature are improved by the additional extraction of 20 kg. However, the peak temperature is still under-predicted. From this study, the clad temperature is sensitive to a small change of the mass inventory in the reactor vessel.

5. Conclusions

A thermal-hydraulic analysis was conducted on the single- and two-phase natural circulations, and reflux condensation mode of the BETHSY facility. The test represented the cooling states of the primary cooling system under the natural circulation for conditions corresponding to the residual power, 2 % of the rated core power value. Based on MARS 1.4 calculations, the major thermal-hydraulic behavior during natural circulation was evaluated, and the discrepancy between the experimental data and calculated results was identified.

The calculated results showed generally good behavior with regard to the single-phase natural circulation, the two-phase natural circulation and the reflux condensation mode; the range of the mass inventory for the single- and two-phase natural circulations, and reflux condensation were predicted properly and the mass inventory of the u-tube empty and the core uncovering were predicted well by the MARS 1.4 code. However, the representation of peak flow in the primary system and the pressure difference between the outlet and inlet sides of the steam generator u-tubes were not predicted appropriately. MARS 1.4 over-predicted the differential pressure in the down-flow side of the steam generator u-tubes at 80 % of the initial mass inventory because the entrained liquid into the down-flow side by the steam velocity were larger than that for the experimental data. From the sensitivity results, the pressure difference in the u-tubes was sensitive to the interfacial drag model. Also, MARS 1.4 over-predicted the differential pressure in the active core at 29 % of the initial mass inventory. As a result, the code did not predict well the rapid increase of the clad temperature at 29 % of the initial mass inventory. The cladding temperature seemed to be very sensitive to the mass inventory in the core.

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