Proceeding of the Korean Nuclear Society Autumn Meeting
Taejon, Korea, October, 2000

Study on System Characteristics under Two-Phase Natural Circulation and Reflux Condensation Conditions

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Abstract

The present study is to assess the applicability of the best-estimate thermal-hydraulic codes, MARS 1.4, for analysis of thermal-hydraulic behavior in PWRs during natural circulation conditions. The code simulates a BETHSY test 4.1a, which was conducted in the integral test facility of BETHSY. The test represents the cooling states of the primary cooling system under two-phase natural circulation and reflux condensation mode with conditions corresponding to the residual power, 2 % of the rated core power value, and a constant pressure of 6.8 MPa at the secondary system. Based on MARS calculations, the major thermal-hydraulic behavior during natural circulation is evaluated and the differences between the experimental and calculated results are identified.

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, the natural circulation is the principal heat removal mechanism following a loss of coolant accident (LOCA) in a loop type PWR (Bae et al., 2000) as well as in a system-integrated modular advanced reactor (SMART) (Bae et al., 1998). In the course of SMART development, natural circulation has been extensively studied at the Korea Atomic Energy Research Institute (KAERI) because of its important role. There are at least three kinds of natural circulation modes, which are single-phase liquid flow, two-phase flow and reflux condensation mode. Two-phase natural circulation may have a significantly enhanced heat transfer capability by allowing boiling in the heating section. However, the instability may lead to a premature boiling crisis and subsequent failure of the heat element. Knowledge of the heat transfer capability, the stability criterion and the response of the system are important for system integrity during natural circulation. Thermal-hydraulic instabilities have been investigated for several decades. Boure et al. (1973) and Lahey and Drew (1980) reviewed prior works and classified the instabilities according to their driving mechanisms, which occurred in a steady state condition. Duffey and Sursock (1987) suggested simple algorithms to predict the flow rate for reflux condensation. Hsu et al. (1998) conducted an experiment for natural circulation and its flow termination under a small break LOCA. It was found that the permanent termination of natural circulation was related to the head balance between the hot and cold sides and the large amplitude flow oscillations occurring near the flow termination condition. The system behavior during natural circulation and the code capability to predict the phenomena need to be studied extensively because of their important nature in the engineering field.

The present study is performed to assess the applicability of MARS 1.4 (Lee, 1999) by comparing the predictions with the BETHSY test results and to understand the system behavior associated with two-phase natural circulation and reflux condensation. 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.

2. Description of the Test Facility and Initial Conditions

Fig. 1 shows a schematic diagram for the BETHSY facility. 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 transients. It consists of a reactor vessel, three primary coolant loops and secondary systems including feed and steam lines. Each primary loop includes a hot leg, a SG, a crossover leg, a reactor coolant pump and a cold leg. A more detailed description of the facility can be found in reference [Bazin] (1987). In BETHSY test 4.1a (Bazin, 1990), 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 SG with three SGs available. After the initial condition was established, the test was performed by draining the mass inventory from the bottom of the vessel and each stage was stabilized for a sufficient period to extract reliable data. 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 reflux condenser mode.

The test is simulated by MARS 1.4, which is a modified version improving the deficiency of the multi-dimensional thermal-hydraulic system analysis code, MARS 1.3.1 (Jeong et al., 1999). Fig. 2 shows the nodalization of the MARS code used for modeling the test facility. 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, SG 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 (RCP) is modeled using a branch component and the pressure drop is adjusted at the RCP by the artificial increasing of a form loss. Heat structures such as SG U-tubes where heat transfer occurs between two fluid volumes are modeled properly.

To simulate a natural circulation event, the system conditions should be determined accurately, which is provided as the initial conditions for the transient calculations. The primary cooling system maintains a single-phase liquid natural circulation condition with an initial pressure of 15.5 MPa, with the core power keeping a constant value of 573 kW during the whole transient. The primary cooling system is completely filled with liquid and its temperature at the core inlet is 557 K. The secondary sides of the SGs maintain a water level of normal operation with a pressure and steam temperature of 6.9 MPa and 558 K, respectively. The initial steady state conditions obtained are compared with the measurement data in Table 1. As shown in Table 1, the calculated results agree well with the experimental data within the measurement errors.

3. Calculation Results and Discussion

The major operational map observed for the BETHSY test 4.1a is shown in Fig. 3, which is the primary system mass inventory excluding that in the surge line and pressurizer for constant power and secondary conditions. The range of inventory investigated is about 83~29 % of its initial value for two-phase natural circulation and reflux condensation. As steam enters the SG u-tubes through the hot leg, a transition from single-phase to two-phase natural circulation occurs when the primary mass inventory is less than 83.5 % of the initial inventory in the experiment. Fig. 4 shows the void fraction in the hot leg. The captions exp. (bottom), exp. (middle) and exp. (top) denote bottom, center and top positions, 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 these results, the experimental void fraction, which is measured at the middle position has nearly the same value as the volume averaged void fraction by the code. And the transition from single-phase to two-phase natural circulation is calculated at the right mass inventory.

Fig. 5 shows the mass flow in the downcomer for various mass inventories. Start-up of the two-phase natural circulation mode is accompanied by an increase in mass flow which reaches a maximum value at 83~84 % of the initial inventory in the experiment. The peak flow is ascribed to an initial increase in the driving force by the void formation in the core. The experimental results agree reasonably well with the other experimental data (Duffey and Sursock, 1987). A temporary reduction in the core inlet flow increases enthalpy, which in turn reduces the average density. This influences the hydraulic pressure difference over the core section. The opposite mechanism occurs in the SG u-tubes. A small change in the mass flow significantly influences steam condensation. 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. The calculated mass flow shows different behavior from the experimental results at 79.5 % of the initial mass. The calculated peak flow is 14.1 kg/s at 79.5 % of the initial mass, while the experimental value is 12.8 kg/s at 83.5 %. The over-prediction of the peak mass flow by about 10 % observed in the calculation is partly due to the pressure loss in the loop, which is related with the interfacial drag. Also, the code does not appropriately predict the mass inventory, in which the peak flow occurs. The pressure difference between the heat source and heat sink is a main driving force for two-phase natural circulation. Fig. 6 shows the pressure difference between the outlet and inlet sides of the u-tubes. At 79.5 % of the initial mass, the liquid distribution in the down-flow side of the SG 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; i.e. larger voids are located in the upper part of the down-flow side for the experiment. The differential pressure of the down-flow side is relatively over-predicted at 79.5% of the initial mass inventory by the MARS code, though the overall differential pressures at the u-tubes agree well with the experimental data as shown in Figs. 7 and 8. Captions exp. (long tube) and exp. (short tube) denote the differential pressure at the longest and shortest u-tubes in the BETHSY facility, respectively. The code well predicts the empty timing of the liquid in the SG u-tubes. The discrepancy of the pressure difference represents that MARS predicts a poor liquid distribution at 79.5 % of its initial mass inventory. This may be caused by various factors such as interfacial drag, condensation, two-phase hydraulic friction loss, etc. Below 39 % of the initial mass inventory, 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.

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 63.3 % of its initial value. The mass flow at these mass inventories is too low for two-phase natural circulation and too high for reflux condensation, which takes place in the SG u-tubes. As the mass inventory further decreases, the flow in the primary cooling system develops to a 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. Fig. 9 shows the calculated liquid flow in the hot leg. The experiment did not measure the flow rate in the hot leg. In the calculation, the liquid mass flow has a slightly negative value with large fluctuations from 58 % of the initial mass inventory. The negative value of the average liquid flow indicates that reflux condensation occurs in the SG u-tubes. The liquid flow maintains a uniform value after the voids are nearly filled in the hot leg, which the mass inventory reaches 34 % of its initial value. The returned mass flow by reflux condensation is about 0.07 kg/s for each loop in the stable condition, in which corresponds to 3 % of the initial loop mass flow as shown in Table 1 and Fig. 5.

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. Figs. 10 and 11 show the differential pressure in the active core and the temperature distribution of the heated rod at 2.8 m from the bottom of the active core, respectively. 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. 10. Fig. 12 shows the mass inventory in the vessel only. The mass inventory in the vessel is slightly over-predicted in the final two stages though the difference between the experimental and calculated results are kept within the bounds of the measurement error range. From this result, the mass inventory in the vessel is very sensitive to the clad temperature.

4. Summary

A thermal-hydraulic analysis was conducted on the two-phase natural circulation and reflux condensation mode using BETHSY experimental data. The test represented the cooling states of the primary cooling system under natural circulation for conditions corresponding to residual power, 2 % of the rated core power value, and a pressure of 6.8 MPa at the secondary system. Based on MARS calculations, the major thermal-hydraulic behavior during natural circulation was evaluated, and the difference between the experimental and calculated results was identified. The calculated results showed generally good behavior with regard to the two-phase natural circulation and the reflux condensation mode. The region of two-phase natural circulation is 83~63 %, reflux condensation mode occurred below 58 %, and an uncovering of the core is obtained at 34 %. However, the representation of peak flow in the primary system and the differential pressure between the outlet and inlet sides of the SG u-tubes was not predicted appropriately at 79.5 % of the initial mass inventory. MARS seemed to over-predict the interfacial drag in the u-tubes. Also, MARS 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 an increase in the cladding temperature. Core heating seemed to be related with interfacial drag. It is necessary to study the effect of the interfacial drag force.

Acknowledgements

This work has been carried out under the Nuclear R & D Program by the Ministry of Science and Technology, Korea.

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Table 1. Initial condition of MARS 1.4 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	558.5
Core outlet temperature, K	573±4	574.1
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 data

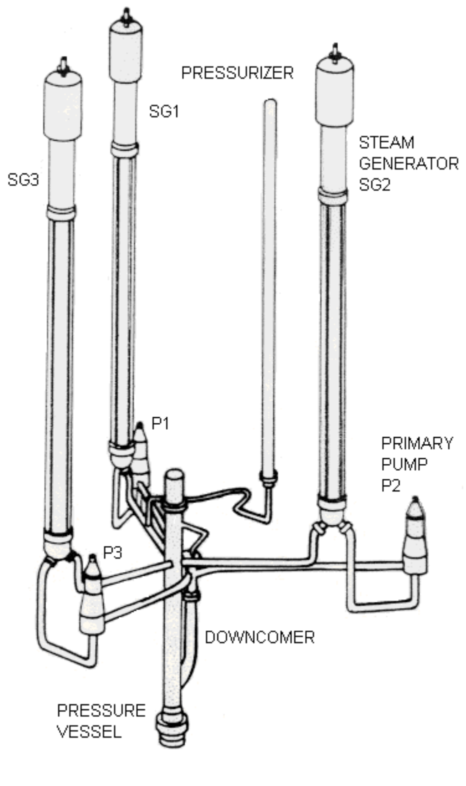

Fig. 1. Introduction to BETHSY test facility.

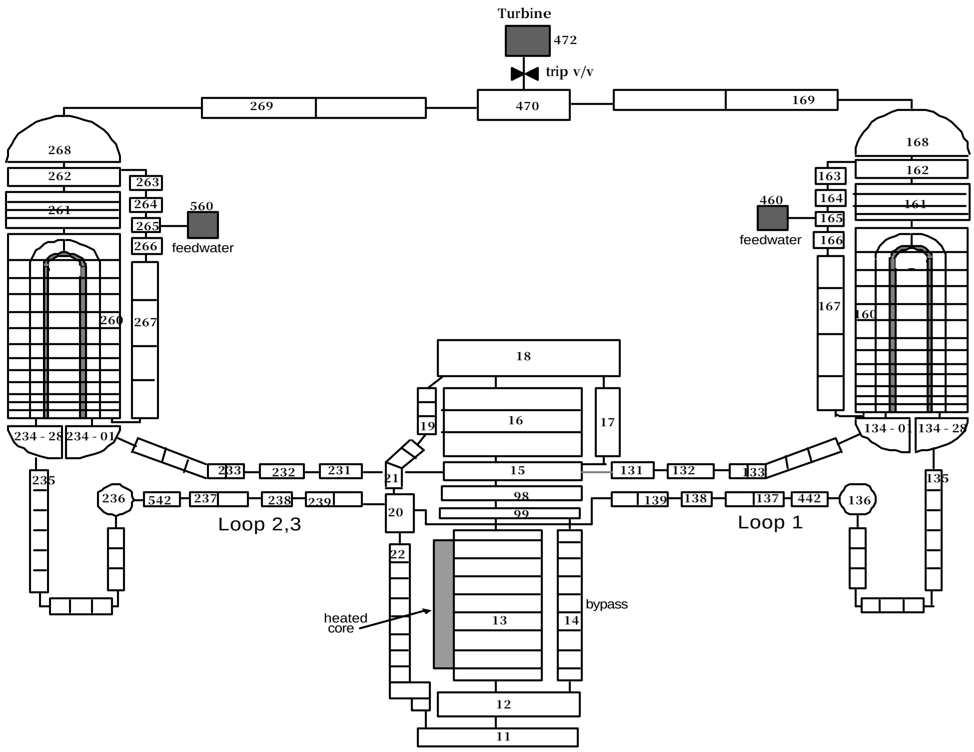

Fig. 2. Nodalization of BETHSY facility for MARS 1.4.

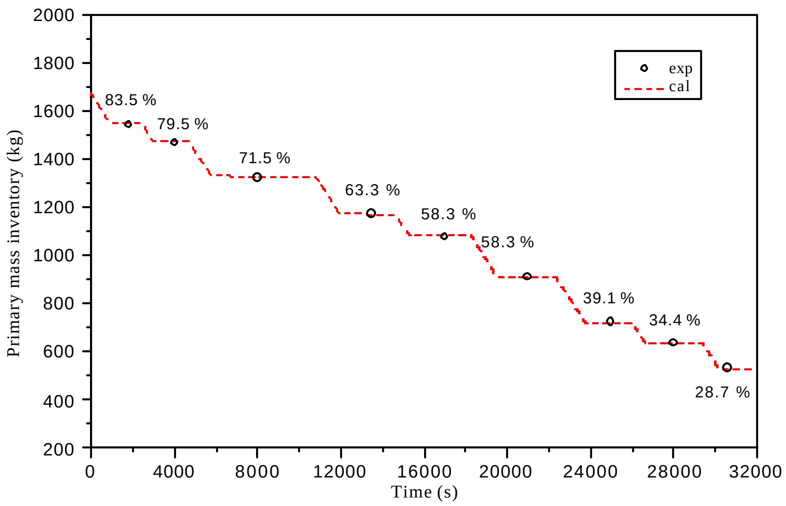

Fig. 3. Mass inventory in the primary system.

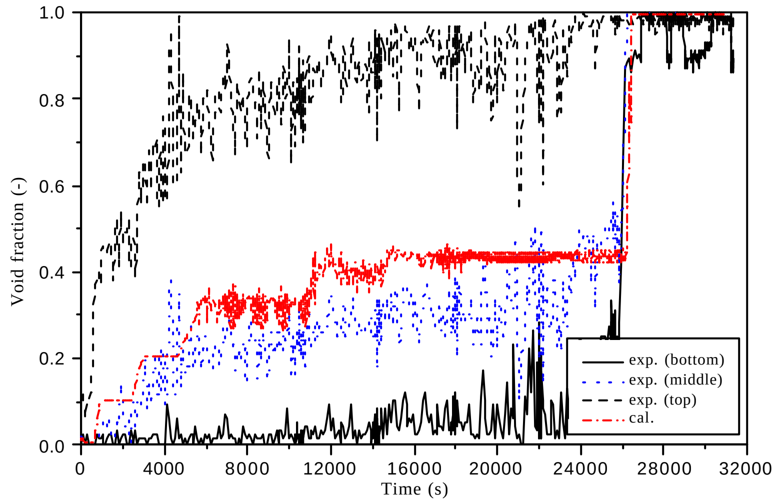

Fig. 4. Void fraction in the hot leg.

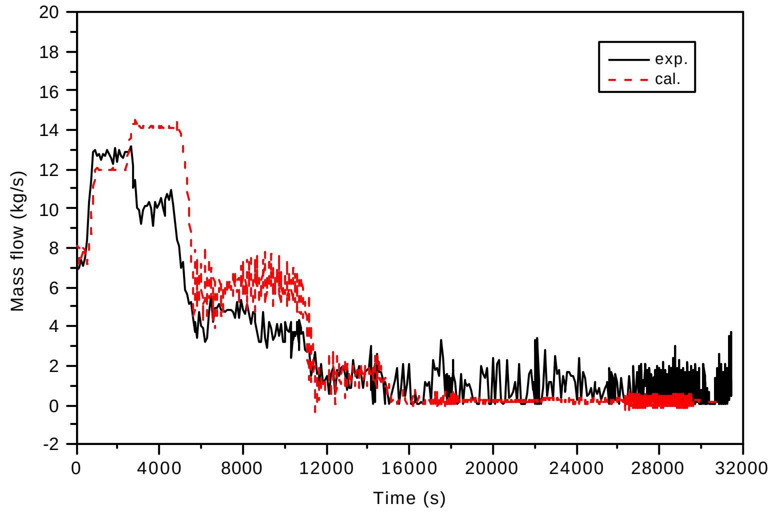

Fig. 5. Mass flow in the downcomer.

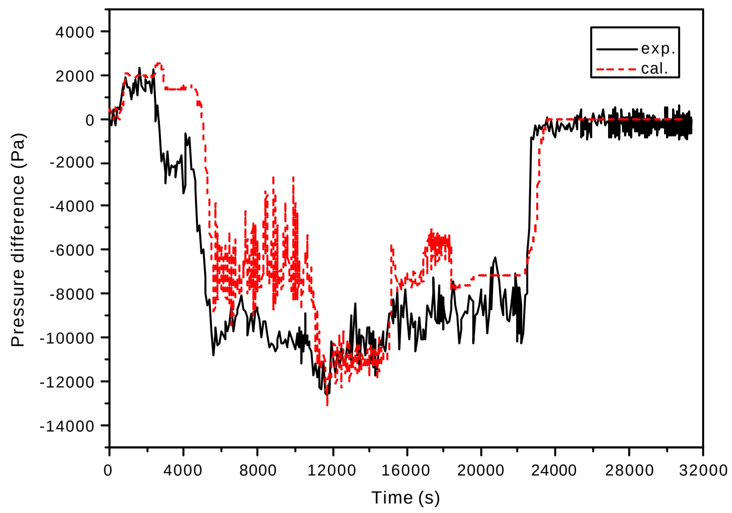

Fig. 6. Pressure difference between outlet and inlet sides of the SG u-tubes.

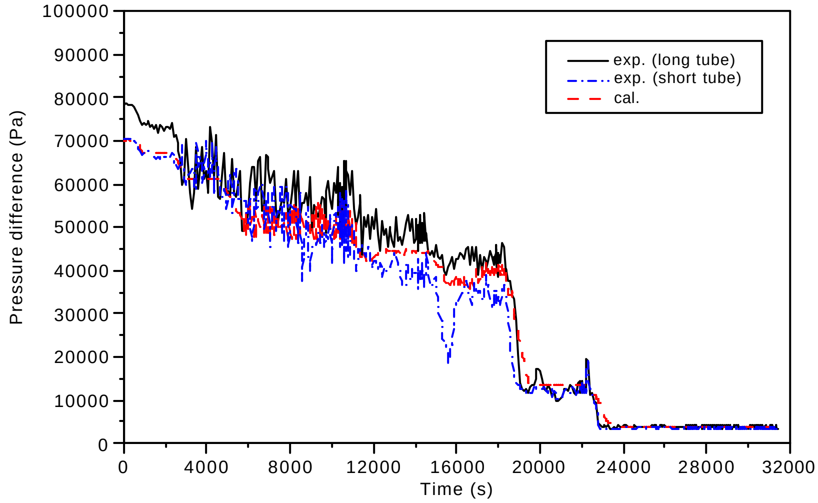

Fig. 7. Differential pressure in the up-flow side of the SG u-tubes.

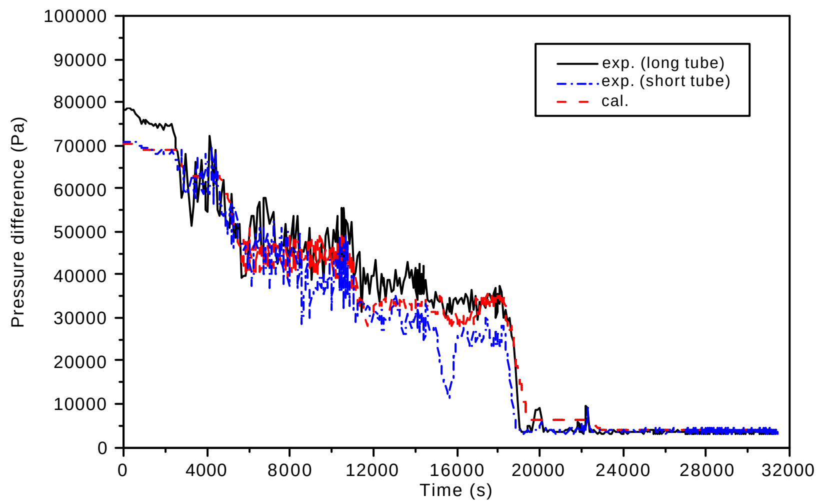

Fig. 8. Differential pressure in the down-flow side of the SG u-.tubes.

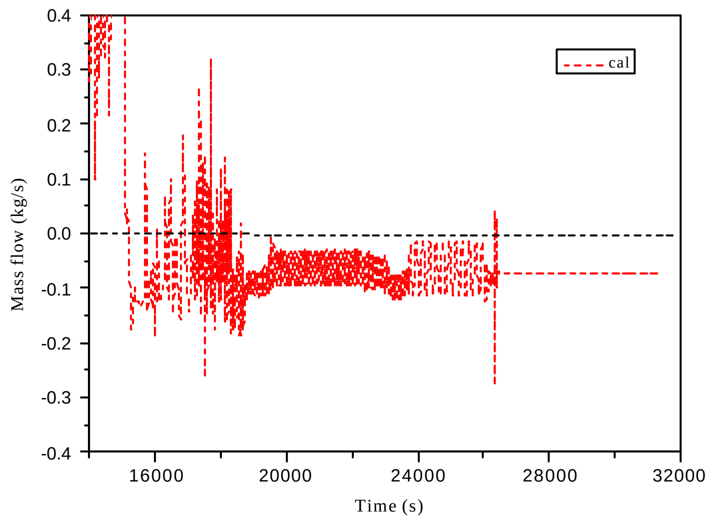

Fig. 9. Calculated Mass flow in the hot leg under reflux condensation.

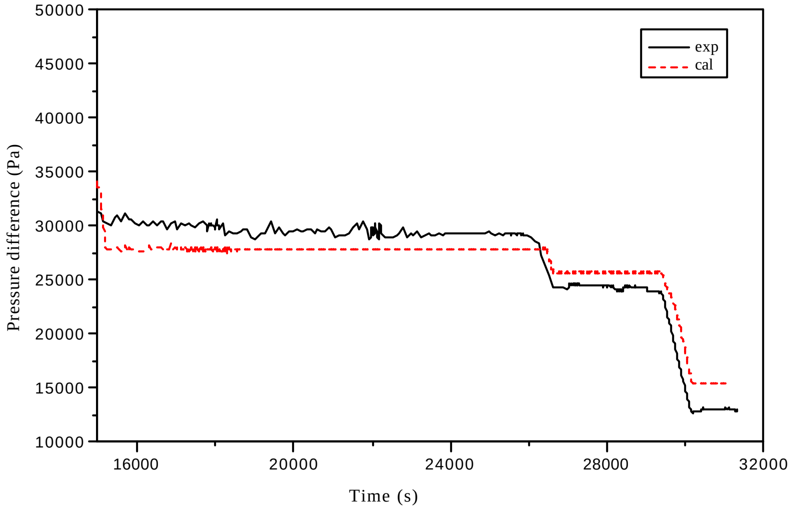

Fig. 10. Differential pressure in the active core under reflux condensation.

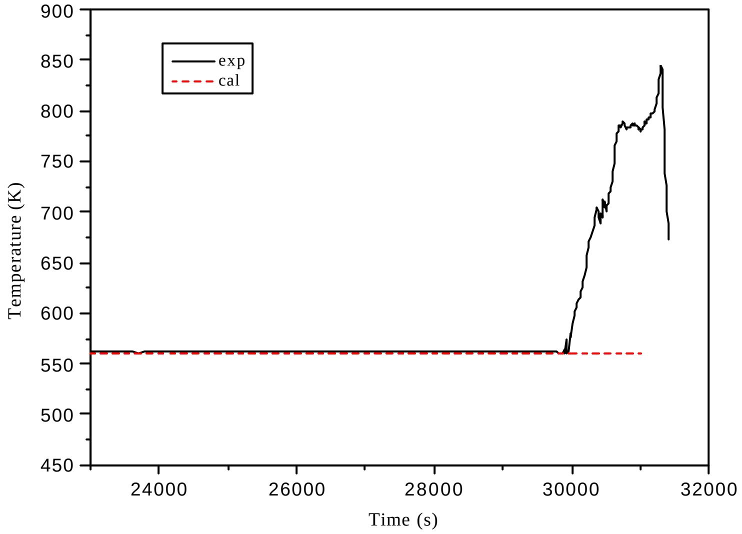

Fig. 11. Peak clad temperature at 2.8 m from the bottom of the active core under reflux condensation

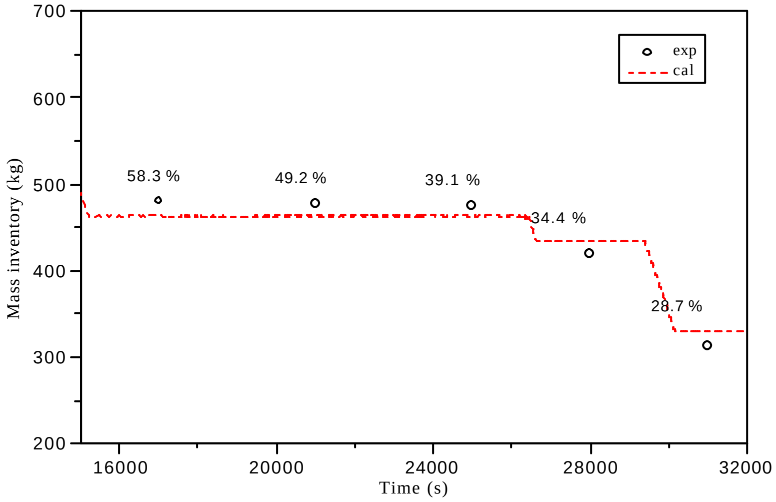

Fig. 12. Mass inventory in the reactor vessel under reflux condensation.