PARAMETERS, WHICH EFFECT THE MASS FLOW IN THE PRHRS UNDER A NATURAL CONVECTION CONDITION

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ABSTRACT

Small and medium sized integral type reactors for the diverse utilization of nuclear energy are getting much attention from the international nuclear community. They diversify the peaceful uses of nuclear energy in the areas of seawater desalination, district heating, industrial heat-generation process and ship propulsion. The SMART (System integrated Modular Advanced ReacTor) is a small modular integral type pressurized water reactor, which was developed for the dual purposes application of seawater desalination and small-scaled power generation in KOREA. The reactor is designed for a forced convection core cooling during start-up and normal operating conditions and for a natural circulation core cooling during accidental conditions. The main safety objective of the SMART is to increase the degree of inherent safety features by advanced designs such as a passive residual heat removal system (PRHRS). The passive residual heat removal system removes the core decay heat and sensible heat by a natural circulation in the case of emergency conditions.

This study focuses on the flow behavior in the passive residual heat removal system of the integral reactor. The system necessitates a hydraulic head to achieve the required natural circulation flow rate, which in turn, may cause a larger two-phase pressure drop and flow oscillation. Also, it is of interest to investigate the complex effects of the boiling and condensation in such low frequency thermo-hydraulic oscillations.

Thermal hydraulic analysis for the passive residual heat removal system has been carried out by means of the MARS code for a full range of reactor operating conditions. The MARS code has been developed at the Korea Atomic Energy Research Institute by consolidating and restructuring the RELAP5/MOD3.2 and COBRA-TF which has the capabilities of analyzing the one-dimensional or three-dimensional best estimated thermal-hydraulic system and the fuel responses of the light water reactor transients.

A selected load to analyze the thermal hydraulic characteristics is 100% of nominal power for a forced convection and 4% for a natural convection conditions. The 4% power natural convection condition is achieved through reducing the primary mass flow, closing the main feedwater and steam isolation valves, and opening the PRHRS isolation valves. Parameters are investigated to find the effect of the mass flow on the passive residual heat removal system under natural convection conditions. The stability regimes are identified by the disturbance amplitude of the transient parameter. If the disturbance amplitude is less than ±3%, the regime is a stable regime, more than ±5% it is an unstable regime, and between ±3% and ±5% it is considered to be a transition regime.

The mass flow behavior in the passive residual heat removal system is divided into four types depending on the fluid state in both the heat exchanger and the emergency cooldown tank. The disturbance amplitudes of the mass flow are more stable with a decreasing of the height between the steam generator and the heat exchanger, and increasing the hydraulic resistance. And the effect of the initial pressure and N_2 fraction in the compensating tank, and the valve actuation time is small or negligible.

1 INTRODUCTION

Small and medium sized nuclear reactors have received increased interest and attentions from the worldwide nuclear industries due to their noticeable merits and advantages in their safety and applications [5]. They diversify the peaceful uses of nuclear energy in the areas of seawater desalination, district heating, industrial heat-generation process and ship propulsion. The SMART (System integrated Modular Advanced ReacTor) is a small modular integral type PWR (pressurized water reactor), which was developed for the dual purposes application of seawater desalination and small-scaled power generation [2].
SMART is a relatively small-sized advanced integral PWR that produces 330 MW of thermal energy under full power operating conditions. The prominent design feature of SMART is the adoption of an integral arrangement. All the primary components such as the pressurizer, main coolant pumps, control element drive mechanisms and steam generator are assembled in a single reactor pressure vessel. Twelve helically coiled, once-through type steam generator cassettes are located at the circumferential periphery between the core support barrel and the reactor pressure vessel. The reactor coolant, forced by 4 main coolant pumps installed vertically at the top of the reactor pressure vessel, flows upward through the core and enters the shell side of the steam generator from the top of the steam generator. The large volume in the top part of the reactor pressure vessel is used as a self-pressurizer, which controls the reactor coolant system pressure by partial steam and gas pressures that vary correspondently with the change of the coolant temperature. Surgelines connecting the inside and outside of the pressurizer are also installed inside the vessel. While the overall arrangement of the reactor coolant system could be simplified by the elimination of the primary piping systems. The secondary feedwater comes into the helically coiled tube side from the bottom of the steam generator, flows upward to remove the heat from the shell side, and then exits the steam generator in a superheated steam condition.

The defense-in-depth concept is incorporated for the control of the SMART plant behavior using inherent and engineered safety features. The inherent safety features of SMART are implemented in the design of a low core power density for a low fuel element temperature rise under accident conditions, design of the core with a sufficiently large negative moderator temperature coefficient due to the soluble boron free core and design of an integral type reactor to eliminate the large primary coolant pipes therefore the large LOCA (loss of coolant accident) elimination.

The passive residual heat removal system (PRHRS) passively removes the core decay heat and sensible heat by a natural circulation in the case of an emergency such as a steam extraction, unavailability of feedwater supply, and station black out. The passive residual heat removal system may also be used in the case of a long-term cooling for repair or refueling works. This system is designed to keep the core undamaged for 72 hours without any corrective actions by operators during the postulated design basis accidents. In case of SMART normal shutdown, the residual heat is removed through the steam generator to the heat exchanger in the emergency cooldown tank. Since it operates at a medium pressure of 3~4 MPa, two-phase flow instability is a difficult problem. The design must eliminate the flow instability and the system has to demonstrate that flow instability does not occur [7][8]. This study focuses on the flow behavior in the passive residual heat removal system of the SMART. This necessitates a high hydraulic head to achieve the required natural circulation flow rate, which in turn, may cause a larger two-phase pressure drop and flow oscillation. Also, it is of interest to investigate the complex effects of boiling and condensation on such low frequency thermo-hydraulic oscillations.

Flow stability is of particular importance in a water cooled reactor, a steam generator, and a heat exchanger. It is undesirable in a boiling, condensing, and other two-phase flow processes. Sustained flow oscillations may cause a forced mechanical vibration of the components and system control problems [6]. Also, flow oscillation affects the heat transfer characteristics and may induce a boiling crisis. A temporary reduction of the inlet flow in a heated channel increases the rate of the enthalpy rise, thereby reducing the average density. This disturbance affects the pressure drop as well as the heat transfer behavior [1]. For certain combinations of a geometrical arrangement and operation conditions, the perturbations can acquire a 180^o out-of-phase pressure fluctuation at the exit, which are immediately transmitted to the inlet flow rate and become self-sustained. For boiling systems, the oscillations are due to the multiple regenerative feedbacks among the flow rate, vapor generation rate, and pressure drop.

2 ANALYSIS MODEL AND INITIAL/BOUNDARY CONDITIONS

Fig. 1 shows a schematic diagram of the passive residual heat removal system, which is connected to the feedwater and steam pipes and consists of a heat exchanger submerged in an emergency cooldown tank, a compensating tank, a check valve and isolation valves. The emergency cooldown tank is located high enough above the steam generator to remove the heat transferred from the primary side of the steam generator by natural convection when the secondary system loses the heat removal capability. The compensating tank makes up the initial inventory loss in the passive residual heat removal system. Following an event, the main feedwater and steam isolation valves are closed, and the isolation valves in the passive residual heat removal system are opened. A closed loop under the natural convection condition is established and the generated heat in the core can be removed through the steam generator in the passive residual heat removal system.

Thermal hydraulic analysis for the passive residual heat removal system of the SMART has been carried out by means of the MARS code [4]. The MARS code has been developed at the Korea Atomic Energy Research Institute (KAERI) by consolidating and restructuring the RELAP5/MOD3.2 [3] and COBRA-TF [9], which has the capabilities of analyzing the one-dimensional or three-dimensional best estimated thermal-hydraulic system and the fuel responses of the light water reactor transients. The basic code structure adopts a one-dimensional geometry and consists of a general purpose steady state and a transient calculation. A volume and junction network models the system response. The volume encloses control volumes, which represent a fluid mass and energy. The junction connecting the volumes represents a fluid momentum and has no volume. The thermal-hydraulic model is formulated with six one-dimensional conservations. The conservation variables are mass, momentum, and energy. The mass and energy for the liquid and the steam including the gas are calculated for each volume, and the momentum is calculated for each junction. There are correlations for the forced and natural convection calculations. The turbulent forced convection heat transfer for a helically coiled and a straight tube is the Mori-Nakayama and Dittus-Boelter correlation, respectively and the natural convection is the Churchill-Chu correlation, which is reported to be valid over the full laminar and turbulent range. Also, the nucleate boiling correlation proposed by Chen has a macroscopic convection term plus a microscopic boil term. A wall condensation model is used for the maximum value between the Nusselt correlation for the laminar flow and the Shah correlation for the turbulent flow with a diffusion calculation when a non-condensable gas is present.

MARS nodalization of the passive residual heat removal system is shown in Fig. 2. The modeling of the passive residual heat removal system used in the thermal hydraulic analysis consists of a steam generator, a compensating tank, a heat exchanger, an emergency cooldown tank, pipes and valves. Best estimated initial and boundary conditions as well as realistic assumptions are employed to evaluate the characteristics of the passive residual heat removal system of the SMART. The major parameters used for an analysis are shown in Table 1. The normal heat transfer and feedwater flow rate are assumed to be 100% of the nominal values. The pressure of the primary and secondary sides in the steam generator are chosen as 15 MPa and 3.5 MPa, respectively.

3 RESULTS AND DISCUSSIONS

The analysis is divided into two groups to obtain the thermal hydraulic phenomena under normal operating conditions; the effects of various parameters such as the height between the steam generator and the heat exchanger, hydraulic resistance, valve actuating time, etc.

A Selected load to analyze the thermal hydraulic characteristics is 4% for the natural convection conditions. The 4% power natural convection from the 100% power forced convection conditions is achieved through reducing the primary mass flow, closing the main feedwater and steam isolation valves, and opening the PRHRS isolation valves as shown in Fig. 1.

Fig. 3 shows the heat removed in the passive residual heat removal system after the main feedwater and steam isolation valves are closed. The heat transferred to the secondary side in the steam generator is high at the beginning of the transient. As the primary power decreases to the power level of 4%, the heat balance between the steam generator and the heat exchanger in the passive residual heat removal system is established and the passive residual heat removal system maintains a stable condition. 45% and 55% of the total heat is extracted from the steam generator by a single-phase liquid and boiling heat transfer, respectively under a natural convection condition. Then, 66% and 34% of the extracted heat is removed at the heat exchanger in the emergency cooldown tank by condensation and a single-phase liquid heat transfer.

Fig. 4 shows the differential pressure between the inlet and outlet sides of the steam generator. It is observed that the differential pressure oscillates periodically with a small amplitude for the natural convection condition. The total differential pressure oscillates periodically with the time-averaged mean value of 15 kPa in the steam generator and the differential pressure of 5 kPa, which is 33% of the total differential pressure, takes place in the orifice. The orifice at the inlet of the steam generator is installed to protect against flow instability. Those values of the present study generally agree with the design values though they should be verified by experimental data. Also, the differential pressure has an effect on the mass flow at the steam generator inlet as shown in Fig. 5. The major behavior of the mass flow for the natural convection condition is divided into four types depending on the fluid state in both the heat exchanger and the emergency cooldown tank because the heat source in the steam generator is constant for the present study. Although the time averaged mean differential pressure is nearly the same value, there are three natural circulation modes. First, the liquid temperature in both the heat exchanger outlet and the emergency cooldown tank increases with the time. Second, both the liquid temperatures maintain a nearly constant value. The liquid in the emergency cooldown tank is a slightly sub-cooled state and the void begins to generate at the top of the tank. Third, the liquid condition at the heat exchanger outlet is the same condition as that of the previous period, however the liquid temperature is a saturated state in the emergency cooldown tank and the void generates from the middle of the tank. The passive residual heat removal system can remove the transferred heat from the primary side in the steam generator as long as the heat exchanger is submerged in the refueling water storage tank.

Some parameters are investigated to find the effect of the mass flow on the passive residual heat removal system under natural convection conditions.

Height between the steam generator and the heat exchanger: The effective height between the steam generator and the heat exchanger in the passive residual heat removal system is one of the most important parameters affecting the natural circulation flow. In this study, the heat transferred from the primary side of the steam generator, the hydraulic resistance in the closed loop, the valve actuation time and the initial compensating tank pressure are constant values with only the height being allowed to change to find the effect. The change in the effective height by –0.5 m, 0.5 m and 1.0 m based on the reference case is investigated. Fig. 6 shows the mass flow at the steam generator inlet. Under the natural convection condition, the time averaged mean mass flow and the amplitude increase as the effective height increases. The steam generator outlet temperature remains at the saturated steam condition of its pressure and the temperature difference between the outlet and inlet sides in the steam generator decrease with the height since the heat transferred from the primary side of the steam generator is constant.

Hydraulic resistance: The hydraulic resistance affects deeply the flow oscillation. In order to maintain the flow condition in the normal operating state, the hydraulic resistance increases only at the passive residual heat removal system. Increasing the hydraulic resistance should help to stabilize the system as the unstable flow disturbance is dampened. The form loss in the pipes to change the hydraulic resistance is varied by -50% and 50% based on the reference case. The disturbance amplitudes show that the system is stable for a form loss higher than or equal to the reference case and the average mass flow decreases with an increase of the hydraulic resistance as shown in Fig. 7.

Valve actuation time: The effect of the actuation time for the isolation valves in the feedwater/steam pipes and isolation valves in the passive residual heat removal system is performed in this group. The investigated parameter is a stroking time of 10 seconds for all the valves, 5 seconds delay for the main steam/feedwater isolation valves after an actuation signal occurs, and 5 seconds delay for the PRHRS isolation valves. The flow oscillation is unstable for the stroking time of 10 seconds, and the other cases are stable as shown in Fig. 8. The mean flow is affected by the stroking time of the main isolation valves and it is negligible for the 5 seconds delay of the PRHRS isolation valves.

4 CONCLUSIONS

The analysis was performed to obtain the thermal hydraulic phenomena under the natural circulation condition. Thermal hydraulic characteristics for the passive residual heat removal system were carried out using the MARS code. The selected condition is 4% power under a natural convection. Under the natural convection condition, 45% and 55% of the total energy was extracted in the steam generator by a single-phase liquid and boiling heat transfer, respectively. And 66% and 34% of the extracted energy to the secondary side of the steam generator was exhausted at the heat exchanger by the condensation and the single-phase liquid heat transfer.

For the natural convection condition, the mass flow behavior in the passive residual heat removal system is divided into three types depending on the fluid state in both the heat exchanger and the emergency cooldown tank although the time averaged mean differential pressure is nearly the same value. The passive residual heat removal system fulfills well its functions in removing the transferred heat from the primary side in the steam generator when the heat exchanger is submerged in the refueling water storage tank. The mass flow is stable in the design scope with 4% of the nominal power although it oscillates periodically with a small amplitude.

The disturbance amplitudes of the mass flow are more stable with a decreasing of the height between the steam generator and the heat exchanger, and increasing the hydraulic resistance. And the effect of the valve actuation time is small or negligible.

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Table 1 Major design parameters for the PRHRS

Parameter	Design	Calculation
Steam Generator		
Primary operating pressure, MPa	15	15
Primary inlet/outlet temperature, K	583/547	582.5/548.0
Primary mass flow, kg/s	87.5	87.5
Secondary inlet/outlet pressure, MPa	4.53/3.45	4.46/3.46
Secondary inlet/outlet temperature, K	323/555	323.0/555.7
Feedwater mass flow, kg/s	6.0	6.0
Pressure drop at orifice, kPa	600-700	675
Passive Residual Heat Removal System		
System pressure, MPa	3.5	3.6
Mass flow, kg/s	2.5	2.45
Steam/liquid temperature, K	516/373	518.5/393.3
ECT liquid temperature, K	303	303
ECT water volume, m^3	91	91
Compensating tank pressure, MPa	4.5	4.5
Height between SG and Hx, m	4.2	4.2

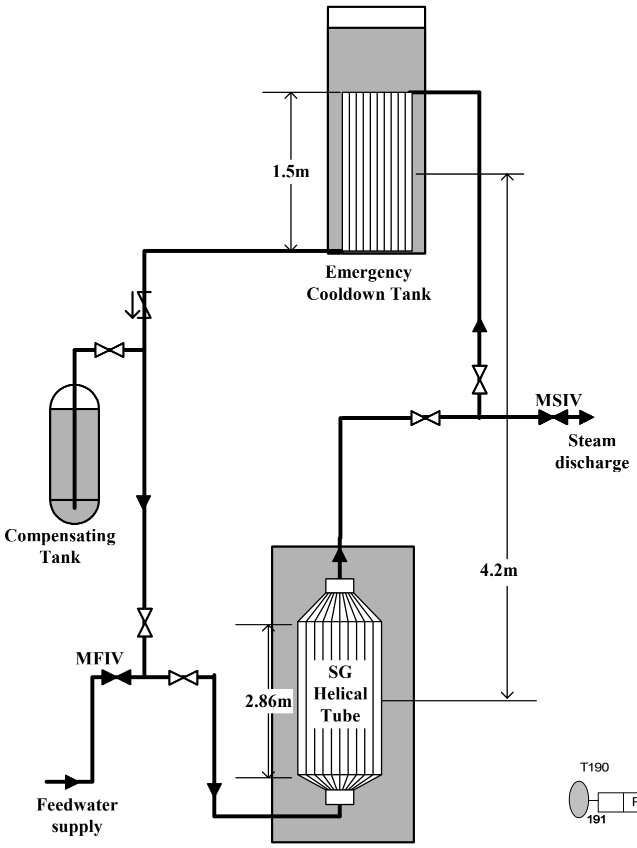

Fig. 1 PRHRS schematic diagram for the SMART

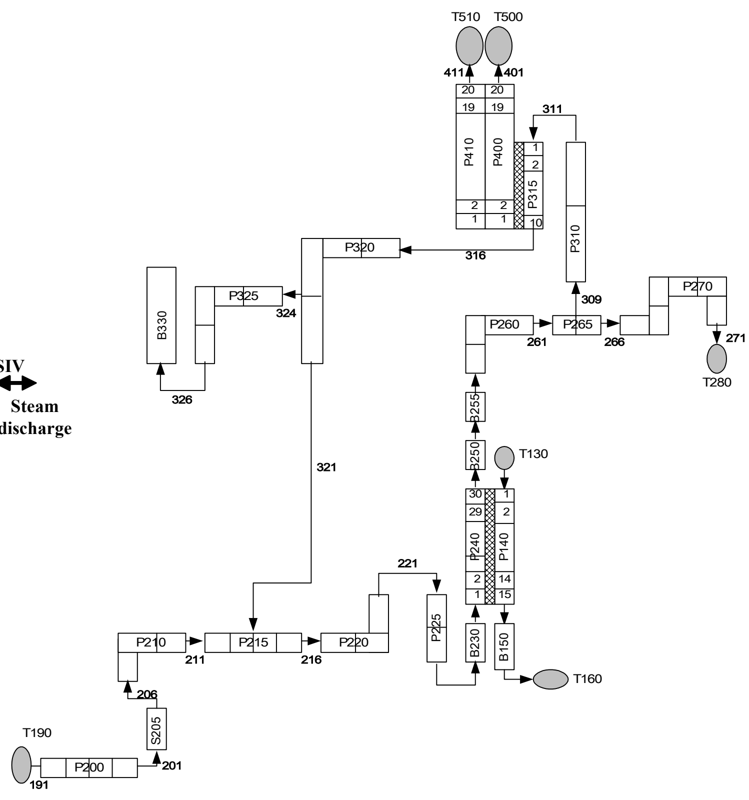

Fig. 2 MARS nodalization for the PRHRS

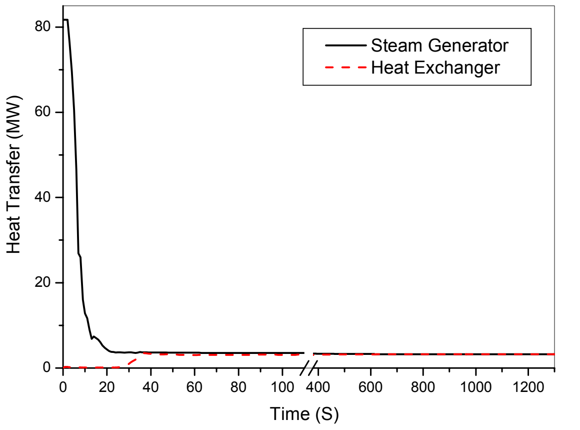

Fig. 3 Heat transfer in the steam generator and heat exchanger

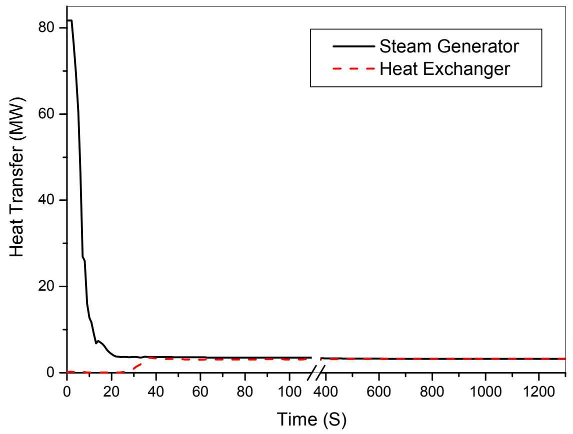

Fig. 4 Differential pressure between the inlet and outlet sides of the steam generator

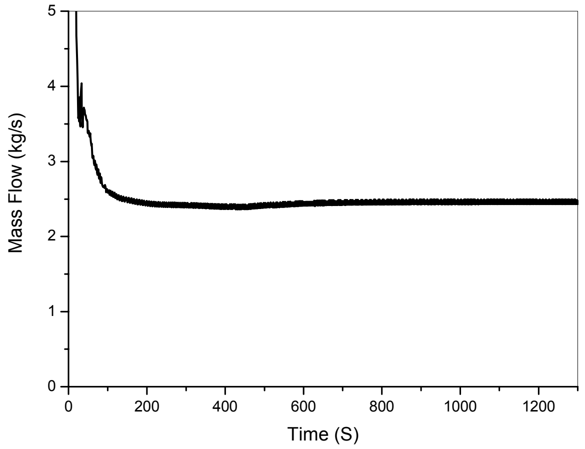

Fig. 5 Mass flow at the steam generator inlet

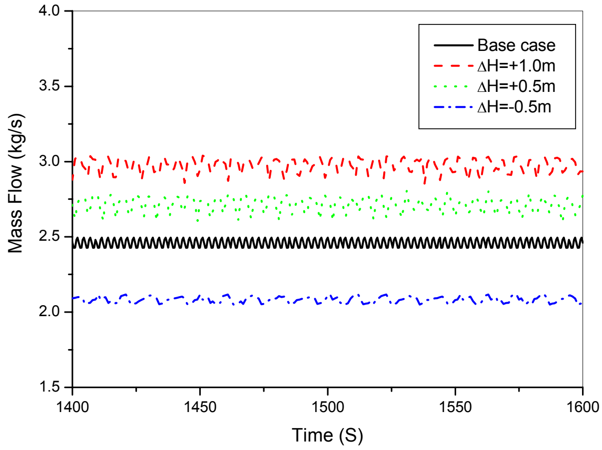

Fig. 6 Steam generator inlet mass flow for the height change.

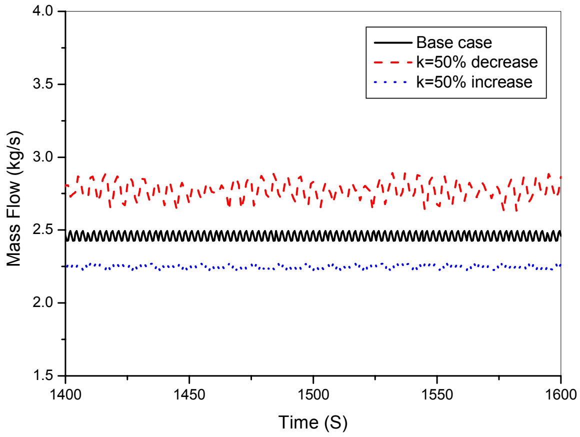

Fig. 7 Steam generator inlet mass flow for the hydraulic resistance change

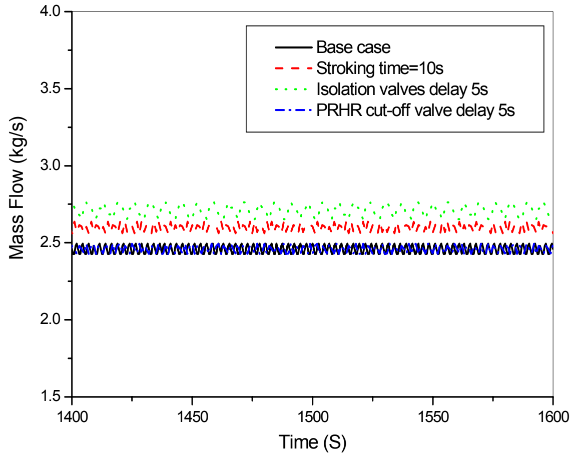

Fig. 8 Steam generator inlet mass flow for the valve actuation time change