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A Study of the Thermo-hydraulic behaviors in the Secondary System of SMART after Reactor Trip

Young-Jong Chung, Hee-kyung Kim, Hee-Cheol Kim and Sung_Quun Zee

Korea Atomic Energy Research Institute
P.O. Box 105, Yuseong,
Daejeon, Korea, 305-600

Abstract

Thermo-hydraulic behaviors for the secondary system in the SMART have been carried out using the MARS code. The SMART is a small modular pressurized water reactor, which is designed for natural convection core cooling during accidental conditions. The MARS is a best-estimate system analysis code based on a two-fluid model for two-phase flows. The selected condition is 100% power under forced convection and 4% power under natural convection. A dominant heat transfer in the steam generator is a nucleate boiling mode under a forced convection condition, and it is a single-phase liquid and a nucleate boiling heat transfer under a natural convection condition. Most heat is removed in the heat exchanger by a condensation heat transfer. The mass flow is stable in the design regimes for the secondary system under the natural convection condition with 4% of the nominal power. The parameter study is predicted considering the effects of an effective height between the steam generator and the heat exchanger, a hydraulic resistance, an initial pressure and a non-condensable gas fraction in the compensating tank, and valve actuation time.

1. Introduction

Small and medium sized nuclear reactors for the diverse utilization of a nuclear energy have received much attention from the worldwide nuclear industries due to their advantages in safety and applications [1]. They diversify the peaceful uses of nuclear energy in the areas of seawater desalination, district heating, heat-generation processes and ship propulsion. SMART (system-integrated modular advanced reactor), which a small sized integral PWR (pressurized water reactor) with the rated thermal power of 330MW is one of those advanced types of small and medium sized nuclear reactors. The basic design of SMART was completed at Korea Atomic Energy Research Institute in March 2002 [2]. The reactor is designed for forced convection core cooling during start-up and normal operating conditions and for 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 PRHRS removes core decay heat and sensible heat by natural circulation in the case of emergency conditions. Also, the system may be used in the case of long-term cooling for repair or refueling. Thermo-hydraulic characteristics under two-phase natural circulation conditions are performed because they are very important for confirming the safety of the plant. Since the secondary system operates at a medium pressure of 3~4 MPa, two-phase flow instability is an important problem. The design must suppress flow instability and a designer has to demonstrate that flow instability does not occur [3].

This study focuses on the flow behavior in the secondary system of the SMART. The system necessitates a hydraulic head to achieve a 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 behavior in such low frequency thermo-hydraulic oscillations. Flow stability is undesirable in boiling, condensing, and other two-phase flow process. Sustained flow oscillations may cause forced mechanical vibration of the components and system control problems [4]. A temporary reduction of the inlet flow in a heated channel increases the rate of enthalpy rise, thereby reducing the average density. This disturbance affects the pressure drop as well as the heat transfer behavior [5].

2. Secondary system of SMART and analysis model

The SMART system prevents core damage and minimizes radiation release to the environment during accidents. The primary components are housed in the reactor pressure vessel. The secondary system consists of feedwater piping lines, steam generator secondary sides, and steam piping lines. The feedwater enters the bottom of the steam generator, flows upward inside the helically coiled tube to remove the heat from the shell side primary coolant and exits the steam generator as superheated steam under normal operating conditions. The PRHRS passively removes core decay heat by natural convection for emergency situations when the normal feedwater supply and steam extraction are unavailable. Fig. 1 shows a schematic diagram of the secondary system and PRHRS. The PRHRS 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 to remove the heat transferred from the primary side in the steam generator by natural convection. The compensating tank makes up the loss of an initial inventory in the PRHRS.

The helical tubes in the steam generator have an inside diameter of 7 mm with a thickness of 1.5 mm and an average length of 9.2 m. A single-phase liquid fluid flows into the bundle side, and a two-phase fluid flows into the tube side in the steam generator cassette. An orifice is installed at the entrance of the steam generator secondary side to maintain flow stability during normal and emergency conditions. The straight tubes of the heat exchanger have an inner diameter of 13 mm with a thickness of 2.5mm and a length of 1.2 m. The heat exchanger elevation above the steam generator is about 3.1 m.

During normal operating conditions, the steam generator header pressure is maintained at 3.5 MPa. Boiling takes place in the steam generator secondary side and the super heated steam leaving the steam generator flows into the turbine. Then, the same mass flow of feedwater enters the steam generator and the flow regime is the forced convection condition. Following an accident, the main feedwater and steam isolation valves (MFIV/MSIV) are closed, and the isolation valves in the PRHRS are opened. A closed loop with the natural convection condition is established and heat can be removed from the primary side of the steam generator using the PRHRS.

Thermal hydraulic analysis has been carried out by means of the MARS code for a full range of reactor operating conditions [6]. The MARS code has been developed at Korea Atomic Energy Research Institute (KAERI) by consolidating and restructuring the RELAP5/MOD3.2 and COBRA-TF codes. The basic code structure adopts a one-dimensional geometry and consists of a general purposed steady state and a transient calculation. A volume and junction network models the system response. There are correlations for 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 has a macroscopic convection term plus a microscopic boiling term.

MARS nodalization of the secondary system and PRHRS is shown in Fig. 2. The modeling 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 conditions are employed to evaluate the characteristics of the secondary system of the SMART. 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 is chosen at 15 MPa and 3.45 MPa, respectively.

3. Results and discussions

The analyses are divided into two parts to find the thermal hydraulic phenomena under normal operating conditions and the effects of various parameters.

3.1 Normal operating condition

A Selected load to analyze the thermal hydraulic characteristics is 100% of nominal power for forced convection and 4% for 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 as shown in Fig. 1. The filled and open symbols of the valve represent the closed and opened state of the valve in the figure, respectively. The stroking time used is 5 seconds for each valve.

Fig. 3 shows the heat removed in the PRHRS 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 PRHRS is established and the PRHRS maintains a stable condition. Under a forced convection condition, a dominant heat transfer in the steam generator is the nucleate boiling mode, which transfers 71% of the total heat. Under a natural convection condition, 45% and 55% of the total heat is extracted in the steam generator by a single-phase liquid and nucleate boiling heat transfer, respectively. Then, 66% and 34% of the extracted heat is removed at the heat exchanger in the emergency cooldown tank by condensation and single-phase liquid heat transfer. Fig. 4 shows the fluid temperature at the inlet and outlet of the steam generator. The fluid temperature difference between the inlet and outlet is 232 K for the forced convection condition of a nominal power. As the power is reduced to 4% from 100%, the fluid temperature difference becomes 142 K for the natural convection condition while the steam pressure nearly maintains the same value of 3.5MPa for the two conditions. The steam at the steam generator outlet has a super steam of 40K for the forced convection and a saturated steam for the natural convection. The degree of the super-steam reduces continuously to the saturation temperature with the beginning of the operation in the PRHRS. Since the flow condition is changed from a forced convection to a natural convection and the core power is decreased a decay heat power level, the mass flow is reduced to about 8.3% of the nominal flow for the natural convection condition although the power decreases to 4% of the nominal power. Fig. 5 shows the differential pressure between the inlet and outlet sides of the steam generator. It is observed that the differential pressure, which maintains a constant value for the forced convection oscillates periodically for the natural convection condition. For a forced convection condition, the total differential pressure keeps on 997 kPa without oscillating in the steam generator and the differential pressure of 675 kPa, which is 68% of the total differential pressure, occurs in the orifice.

The values of the present study generally agree with the design values though they should be verified by experimental data. For a 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 differential pressure has an effect on the mass flow at the steam generator inlet as shown in Fig. 6. 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 condition in the steam generator is constant for the present study. Fig. 7 shows the liquid temperature in the heat exchanger and the emergency cooldown tank, respectively. Although the time averaged mean differential pressure is nearly the same value, there are different natural circulation modes.

3.2 Sensitivity study for a mass flow

Some parameters are investigated to find the effect of the mass flow on the secondary 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 transition regime.

3.2.1 Effect of height between the steam generator and the heat exchanger

The basic parameters for the nominal design are listed in Table 1. The effective height between the steam generator and the heat exchanger in the PRHRS is one of the most important parameters affecting flow oscillation. In this group of studies, 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 unchanged values with only the height being allowed to change to find the effect. The change in the effective height by –16%, 16% and 32% based on the reference case is investigated. Fig. 8 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 height. The regimes are stable in range less than or equal to the reference case.

3.2.2 Effect of valve actuation time

The effect of the actuation time for the isolation valves in the feedwater/steam pipes and in the PRHRS is performed in this group. Other parameters such as the feedawater flow and the heat transferred from the primary side of the steam generator are kept at a constant value. 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. 9. The mean flow is affected by the actuation time of the main isolation valves and it is negligible for the 5 seconds delay of the PRHRS isolation valves.

3.2.3 Effect of hydraulic resistance

Hydraulic resistance affects deeply the flow oscillation. In order to fix the flow conditions for normal operation in the forced convection, an increase of hydraulic resistance in the PRHRS dampens the unstable flow disturbances for the emergency condition. Increasing the hydraulic resistance should help to stabilize the system. The heat transferred from the primary side of the steam generator, the emergency cooldown tank condition, feedwater temperature and flow, the valves actuation time, and the initial compensating tank pressure are fixed for this study. The form loss at the valves 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. 10.

4. Conclusions

Thermo-hydraulic characteristics for the secondary system have been carried out to investigate the stability behavior using the MARS code. The selected condition is 100% power under forced convection and 4% power under natural convection. Under the forced convection condition, a dominant heat transfer in the steam generator is the nucleate boiling mode, which transfers 71% of the total generated heat. Under the natural convection condition, 45% and 55% of the total energy is extracted in the steam generator by a single-phase liquid and nucleate boiling heat transfer, respectively. And 66% and 34% of the extracted energy to the secondary side of the steam generator is exhausted at the heat exchanger by a condensation and single-phase liquid heat transfer.

For the natural convection condition, the mass flow behavior in the secondary system depends 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 emergency cooldown tank. The mass flow is stable for 4% of the nominal power.

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

Acknowledgement

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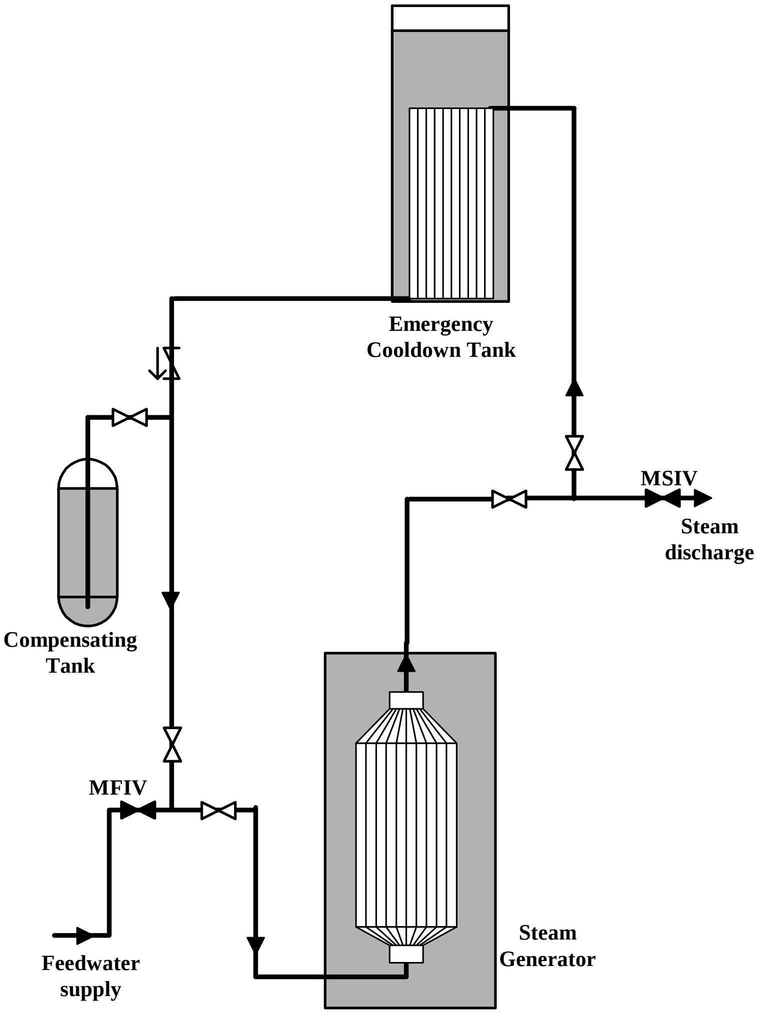


Fig. 1 Schematic diagram of PRHRS for the SMART

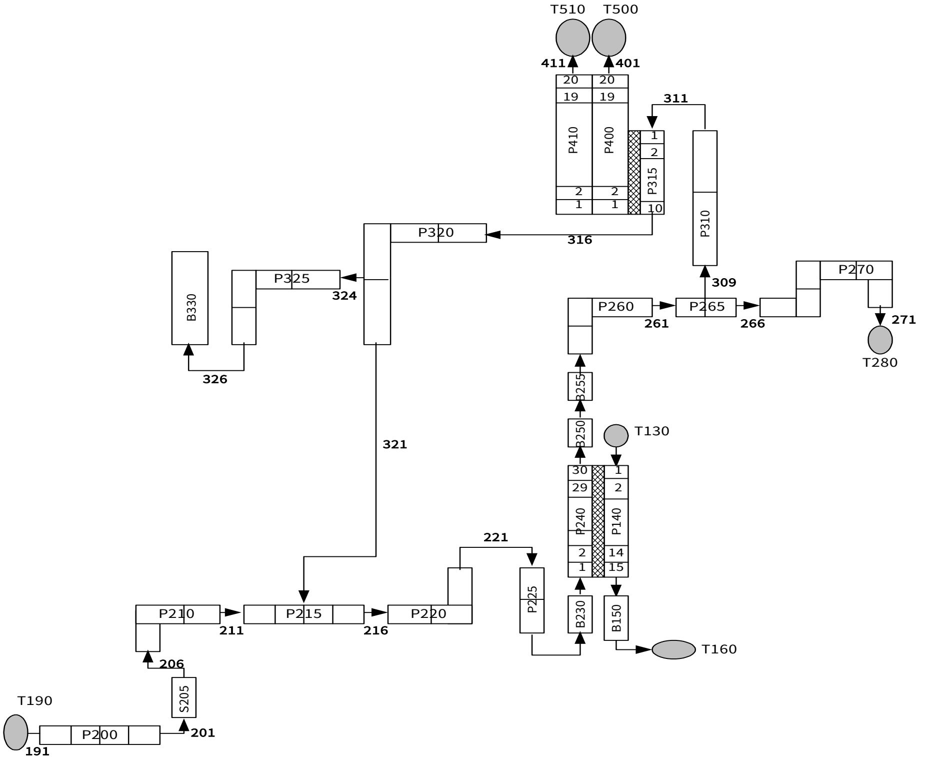


Fig. 2 Nodalization of MARS code

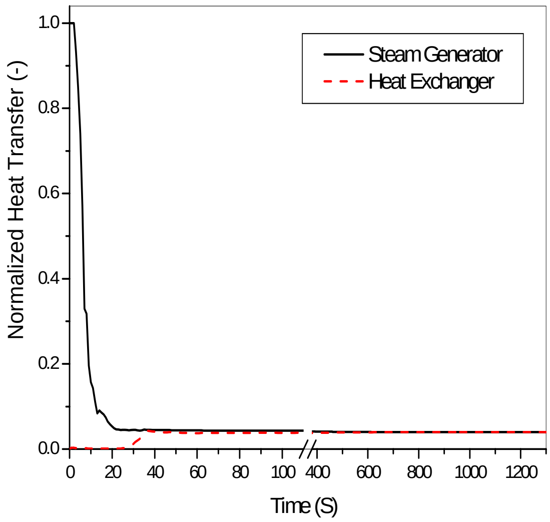


Fig. 3 Heat transfer in the steam generator and heat exchanger

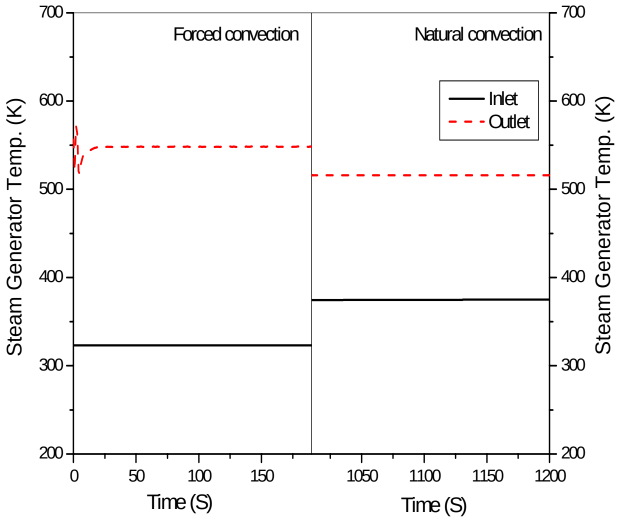


Fig. 4 Fluid temperature in the steam generator

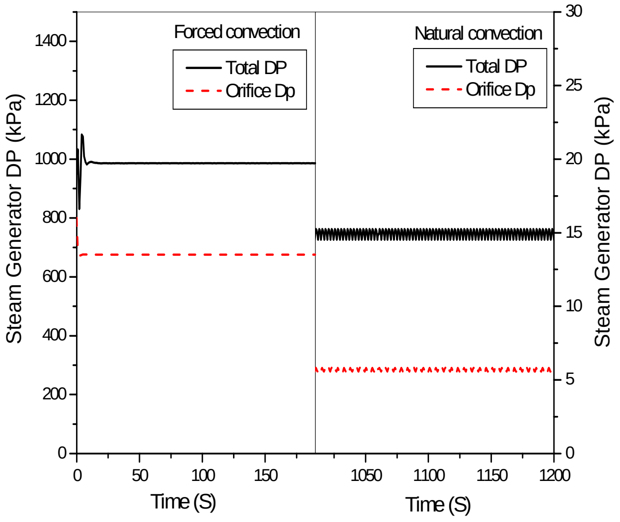


Fig. 5 Differential pressure between the inlet and outlet sides of the steam generator

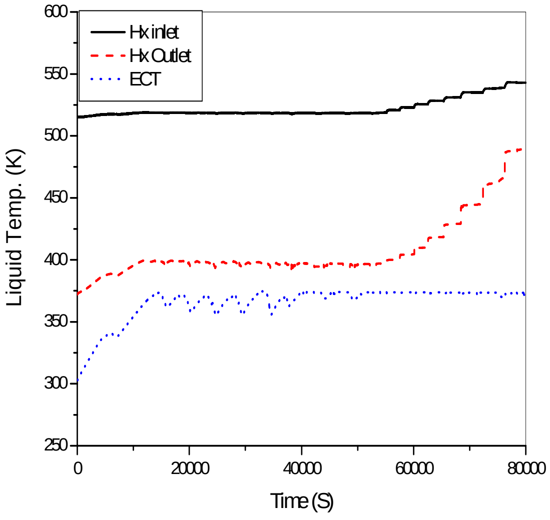
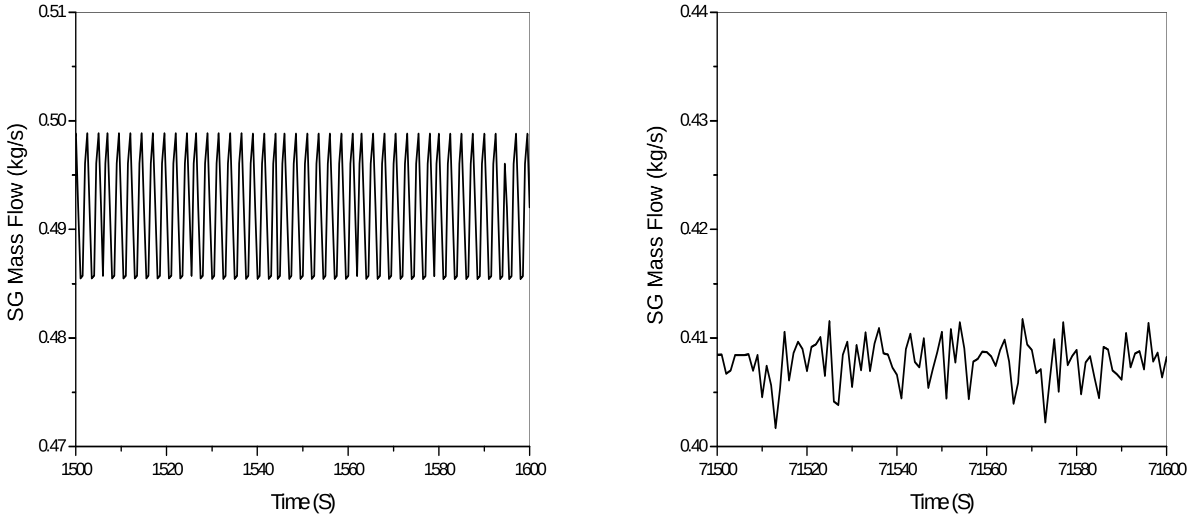


Fig. 7 Liquid temperature at the heat exchanger and the emergency cooldown tank



(a) (b)

Fig. 6 Mass flow at the steam generator inlet

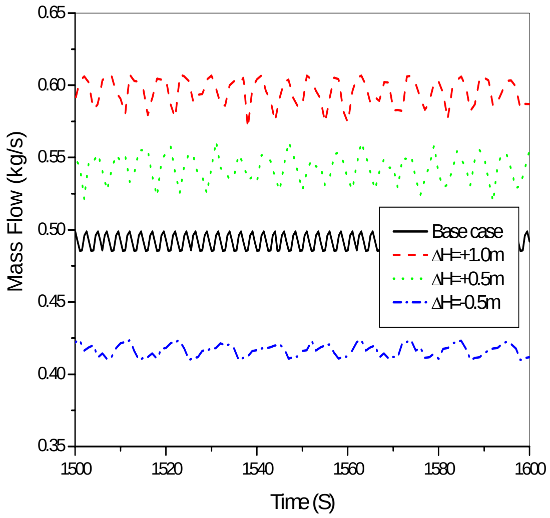


Fig. 8 Steam generator inlet mass flow for the height change

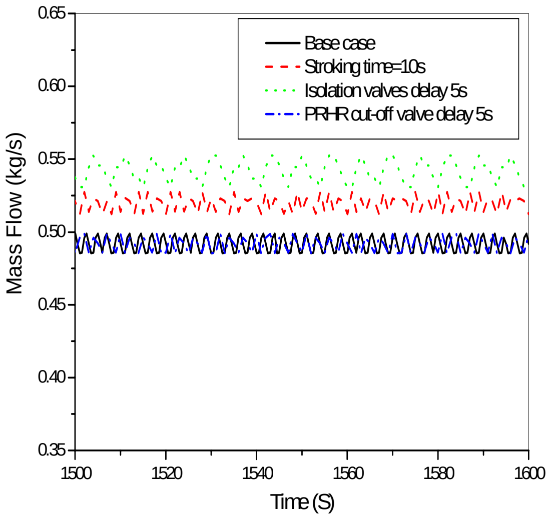


Fig9 Steam generator inlet mass flow for the valve actuation time change

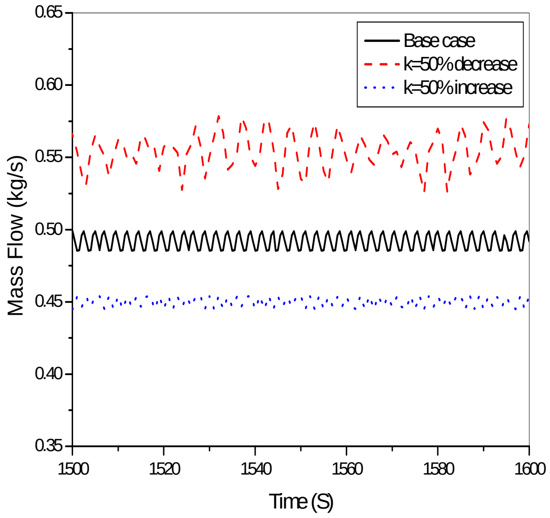


Fig. 13 Steam generator inlet mass flow for the hydraulic resistance change