Extension of MARS-KS Code Based Modeling Scheme, SEMICOM, to Predict the Dynamics of Combined Valve System in PECCS

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1. Introduction

Researches have been conducted to design the recirculation valves and vent valves, which are key components of the Passive Emergency Core Cooling System (PECCS) of Innovative Small Modular Reactors (i-SMR) [1]. Those valves should not only be actuated without power as a passive feature, but should also be actuated automatically by signals, and should be manually actuated by the operator [2, 3]. To comply the requirements, additional components including actuator trip valves are introduced to the main valve, which may cause a concern about a single active failure involved with those components. Also a block valve may be required to prevent inadvertent opening of the main valve. The ECCS valve configuration of the NuScale Design Certification illustrates such an example [4].

In previous studies [5, 6], the authors have developed a modeling method to analyze the dynamic behavior of a spool valve driven by pressure difference and spring force to confirm that one main valve can be operated in passive manner and supply water accumulated in the containment vessel (CV) to the reactor pressure vessel (RPV). In the method, a solver of the equation of motion of a spool using the set of control variables of the system thermal-hydraulic code, MARS-KS [7] was used. Hereafter, the method is referred as SEMICOM (Solution of Equation of Motion Implemented by Control-variables Of MARS-KS).

In the present work, we discuss an extension of the SEMICOM for applying to the complex valve system described above. To this purpose, we construct a virtual valve system considering the PECCS recirculation valve, which include fluid connections with a main valve, a block valve, an actuator trip valve and an actuator reset valve and predict the dynamic behavior of the system. This extension is expected to be used effectively to assess the ability to respond to single active failures such as inadvertent opening of trip valve and failures of block valve closing.

2. Modeling Scheme

2.1 Configuration of combined valve system

The virtual recirculation valve to be discussed in this study consists of one main valve, a block valve, an actuator trip valve and an actuator reset valve, as shown in Figure 1, and the connection of each valve is as shown in the figure. The upper chamber of the main valve is connected to the upper chamber of the block valve, and when the trip valve is opened (due to signal or loss of electric power), water from the upper chambers is released into the CV, which raises the spool of the main valve by a pressure difference, opening the port on the CV side, and recirculating water from the CV to the RPV.

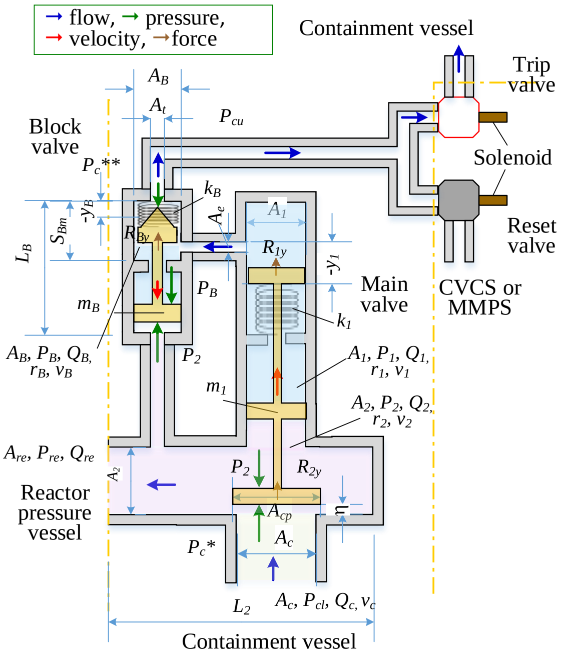

Fig. 1. Configuration of virtual valve system

For the valve system of this configuration, the items to be confirmed through analysis are as follows

1) Maintain the pre-determined disk position of each valve during normal operation,
2) When the containment pressure and water level increase and the RPV pressure decreased and an ECCS signal occurred, the pilot trip valve is connected to the CV, the disks move as desired, and the ECCS flow path is formed,
3) During normal operation, malfunction of the pilot trip valve (forming vent flow towards CV) causes water to release from the block valve,
4) If conditions are formed during ECCS operation, can the pilot reset valve be opened to stop the ECCS (manual stop), and

5) When conditions are formed, can the pilot trip valve be opened to start the ECCS (manual startup)

2.2 Governing equations

As suggested in the previous study, the equation of motion of each spool is solved using the pressures calculated from the MARS-KS code in the SEMICOM method. The equation of motion for two spools of the main valve and the block valve is as follows:

$$m_1\ddot{y}_1 + c\dot{y}_1 + k_1 y_1 = -m_1 g + F_{1p} + R_{1y} + R_{2y} \tag{1}$$

$$m_B\ddot{y}_B + c\dot{y}_B + k_B y_B = -m_B g + F_{Bp} + R_{By} \tag{2}$$

where, m, c, k, F and R mass, viscous damping coefficient, spring constant of spool, force due to pressure difference, and reaction force to changes in the momentum of fluid in the chamber, respectively. Subscripts $1, 2, B, p$ and y represent the upper chamber, lower chamber of the main valve, the block valve, pressure, and vertical direction, respectively. Also, y, $\dot{y}$, and $\ddot{y}$ represent displacement, velocity and acceleration. Terms on the right-hand side of the equations can be derived as follows.

$$F_{1p} = A_1(p_2 - p_1) + A_c({p_c}^* - p_2) \tag{3-1}$$

$${p_c}^* = \begin{cases} a_p(p_2 - p_c)\eta + p_{cl} & for\,\eta < 1/a_p \\ p_2 & for\,\eta \geq 1/a_p \end{cases} \tag{3-2}$$

$$\eta = (y_1 + d_2 - t)/(d_2 - t)$$

$$R_{1y} = -\rho_1\left\{(L_{01} - y_1)\frac{\partial Q_e}{\partial t} - Q_e\dot{y}_1 + Q_e|v_e|\right\} \tag{3-3}$$

$$R_{2y} = -\rho_2\left\{A_2 L_2\frac{\partial v_c}{\partial t} + v_c A_1\dot{y}_1 - Q_c|v_c|\right\} \tag{3-4}$$

$$F_{Bp} = (p_2 - p_B)A_B + (p_c^{**} - p_B)A_t \tag{4-1}$$

$${p_c}^{**} = -d_t(p_B - p_c)y_B + p_{cu} \tag{4-2}$$

$$R_{By} = -\rho_B\left\{A_B(L_{0B} - y_B)\frac{\partial v_B}{\partial t} + Q_B\dot{y}_B - Q_t|v_t|\right\} \tag{4-3}$$

where, $A, L, p, Q, a, v, d,$ and t mean area, length, pressure, volumetric flow rate, user defined constant, velocity, tube diameter, and thickness of disk head, respectively. Subscripts e, c, t denote the block valve upper chamber, containment, and downstream tube to actuator valves. The port connected from the trip valve to containment upper part was designated by cu, thus the containment port to the main valve by cl.

Equations (1) to (4) are simultaneous equations in which pressures in RPV and CV, displacement of each spool, and flow rate at each port are nonlinearly coupled with each other. They are explicitly solved using the pressure, flow rate, and density at each node calculated by MARS-KS code [5, 6].

2.3 MARS-KS modeling

A MARS-KS nodalization for the valve system described above was developed with assumed geometric dimensions (case A), based on the previous work [6]. Five hydrodynamic volumes, including the upper and lower chambers of the main valve, the upper chamber of the block valve, and the connection tubes, were defined, and servo valve components were applied to three ports whose flow area was changed with spools moving. Figure 2 shows the overall MARS-KS nodding for the valve system. The noding used in the previous study [6] was also shown in Figure 3, in which the block valve and the associated components are not modeled (case B). Effect of the presence of the block valve can be estimated through comparison.

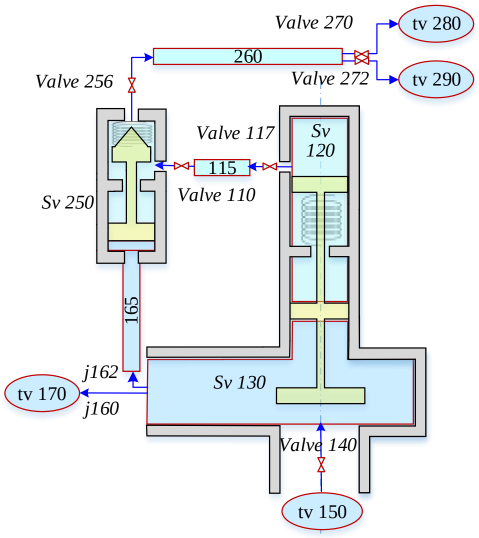

Fig. 2. MARS-KS noding of the valve system (case A)

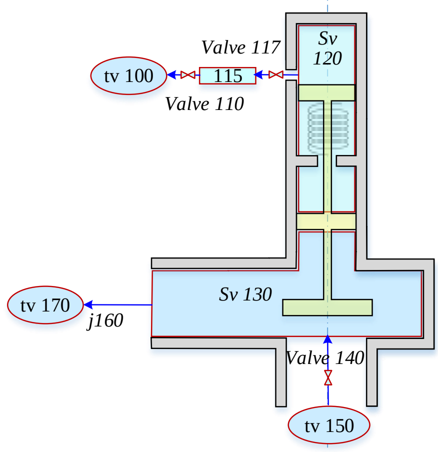

Fig. 3. MARS-KS noding of the single main valve (case B)

3. Results and Discussion

For the cases of virtual valve system (case A) and single valve (case B) described above, calculations were conducted by imposing boundary conditions for pressures with time at the RPV and CV sides, which is based on a loss of coolant accident (LOCA) scenario. Figure 4 shows time-dependent pressure behavior at RPV and CV.

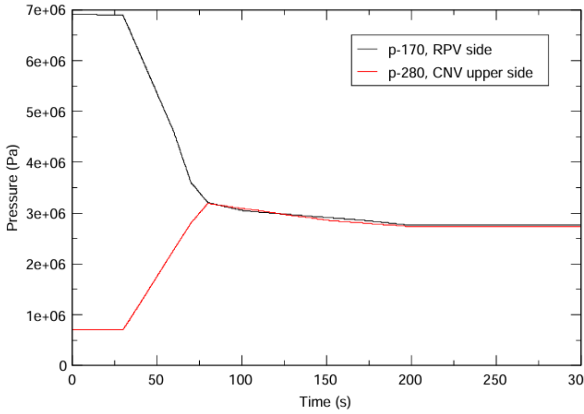

Fig. 4. Pressure boundary condition

Figure 5 shows a comparison of the displacement of spool in main valve between two cases. It shows that the disk of the main valve opens later and smaller in the case A than the case B. This is believed to be due to components that can increase hydraulic resistance on the downstream side of the main valve control port. It delayed the vent time of the upper chamber of the main valve than the case B. In both cases, the displacements approached a stable position after 200 seconds, which is due to the boundary condition with constant pressure after 200 seconds.

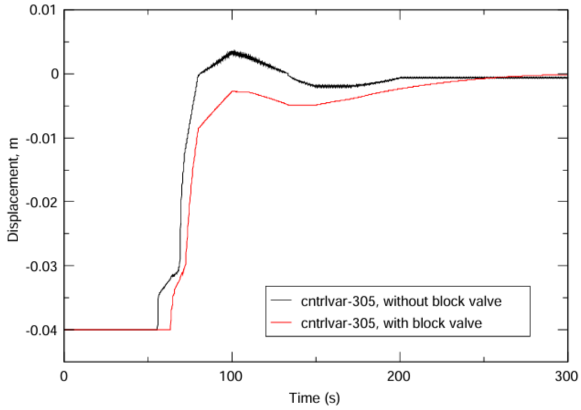

Fig. 5. Comparison of displacement of spool of main valve

Figure 6 compares the pressure in the upper chamber of the main valve between both cases and the pressures in the block valve and downstream pipe for the case A. When the block valve is modeled (case A), it can be seen that the pressure in the upper chamber of the main valve continues to be higher up to 300 seconds than case B. In this figure, the trip valve is actively opened for about 30 seconds by the ECCS signal (CV high pressure or RPV low pressure) and the block valve is passively opened at a similar timing, and the passive opening of the main valve is predicted at about 60 seconds later. It is clearly the effect of the block valve and downstream components, so those effects should be considered in the design.

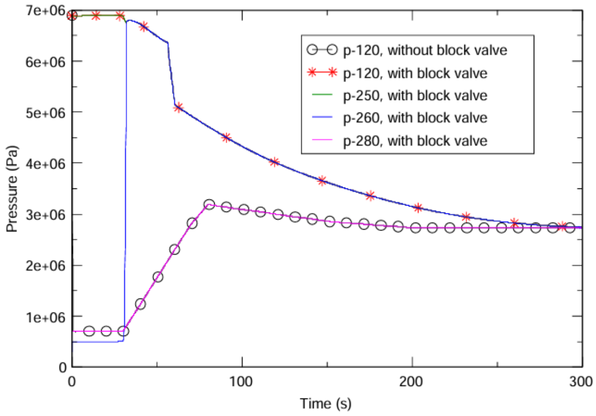

Fig. 6. Comparison of pressures between two cases

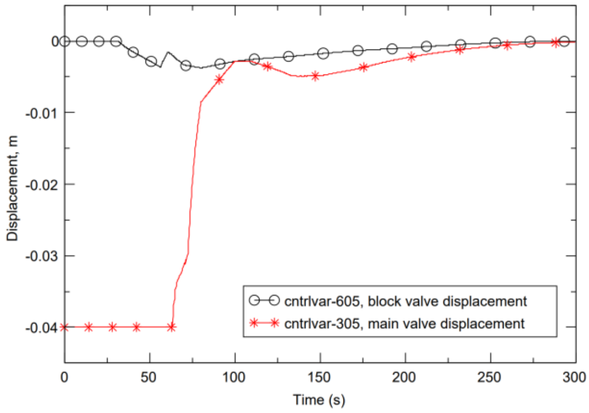

Fig. 7. Comparison of displacements of main valve and block valve

Figure 7 shows the displacements of spools in the main valve and the block valve. The aforementioned contents are confirmed in this figure. On the other hand, it can be seen that the maximum opening displacement of the block valve is very limited compared to the main valve, so it seems that appropriate consideration is needed in the valve design.

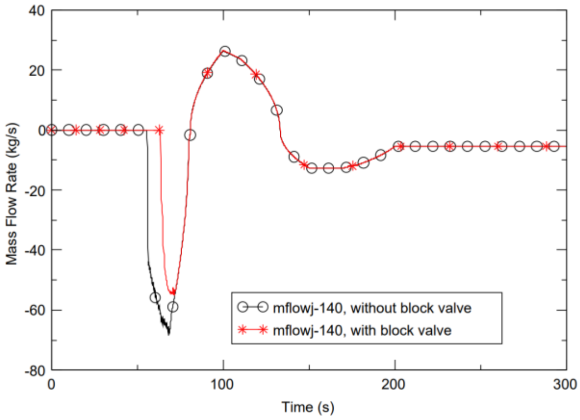

Fig. 8. Comparison of mass flow rates through CV port

Figure 8 shows a comparison of mass flow rates through CV port between two cases. The difference between the two cases is the difference in the flow rate released from RPV to CV at the beginning of the main valve opening, which is clearly due to the difference in opening time of the main valve. Whether those ECCS flows are appropriate should be determined through feedback from accident analysis.

4. Conclusions

In this study, the method of dynamic behavior analysis a single spool valve in the previous study [5, 6], SEMICOM, was extended so that it can be applied to the combined valve system of PECCS of i-SMR. The conclusions obtained through the study are as follows.

1) A block valve, an actuator trip valve, and the associated flow paths connecting the chambers of the valves were implemented to the existing main valve model and the solver of two governing equations for each spool of the main valve and the block valve could be developed as intended.
2) As a result of the application to the virtual valve system, the effect of the increase in hydraulic resistance due to the block valve and its downstream components was identified from the comparison with the single valve model.
3) The extended method could help solve design considerations related to hydraulic resistance, such as differences or delays in the timing of passive opening of the main valve and the block valve, and the degree of opening of the block valve.

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