*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 22-23, 2025*

# Considerations for Performance Parameters in Design of Passive ECCS Valves through Dynamic Response Analysis

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***Keywords :** Passive ECCS valves, Performance Parameters**,** Solution of Equation of Motion, Control Variables, MARS-KS

## 1. Introduction

As discussed in the reference [1], the Passive Emergency Core Cooling System (PECCS) valves to be used for Innovative Small Modular Reactors (i-SMR) is expected to consist of main valve (MV) driven by the pressure difference between the reactor vessel (RV) and the containment vessel (CV), block valve (BV) to prevent improper opening of the MV, and actuator trip valve (ATV) to ensure active actuation. The design of such a valve system needs to determine the several parameters to meet the design requirements and to implement them into actual system effectively. Design requirements include structural parts such as capability on seismic load and hydraulic load, the environmental qualification capability, etc., and performance parts to achieve the required valve opening characteristics [2].

In the performance design part, the process should be carried out for determining the geometric design parameters including the inlet and outlet areas of MV and BV, the piston area of spool, penetrating orifice area, etc., and the kinetic design parameters including the weight and displacement of the spool, spring constant, damping coefficient, etc., which can affect the dynamic response of the valve. Analysis of dynamic response should have sufficient detail and validity to reflect the effects of those parameters.

In this study, we first discuss which parameters should be considered, how those parameters affect the dynamic response, and so in what sequence it is effective to determine them. For the analysis of dynamic response, the SEMICOM (Solution of Equation of Motion Implemented by Control-variables Of MARS-KS) method developed in the authors' previous studies [3][4][5] is applied. Since the configuration of the PECCS valve of i-SMR has not been determined so far, the virtual valve covered in the previous study is targeted.

## 2. Determination of Performance Parameters

### *2.1 Configuration of valve system*

Figure 1 shows a virtual PECCS valve system. As described above, MV, BV, ATV and connection pipe are shown. According to Section 6.3 of Design Specific Review Standards of US Nuclear Regulatory Commission, passive ECCS also requires the active capability to automatically activate by signals, and it can be understood that a solenoid-driven actuator trip valve needs to be installed to meet this requirement. Important geometric design parameters that must be determined in performance design are shown in the figure. The geometric dimensions are indicated based on the closed state of the MV. There are some geometric parameters that are not shown in the figure but can affect the performance, and some of the parameters shown may have little effect on the performance. For the design goal for performance, the parameters related to the spool of the MV and the BV will be determined first, and the remaining parameters will be determined by other design constraints.

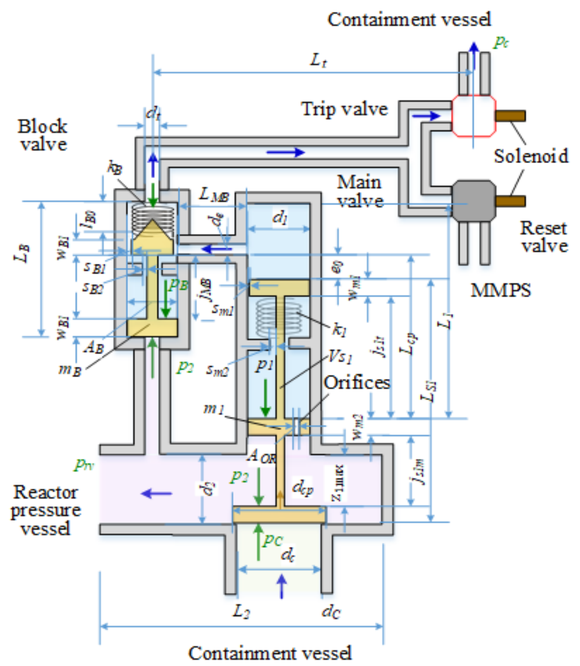


Fig. 1. Configuration of virtual valve system

### *2.2 Performance parameters*

Spool valves have two elements: a cylindrical barrel in which slides a plunger. Port blocking is provided by lands or full diameter sections on the spool, separated by waisted sections which provide port interconnections through the barrel. Therefore, the geometric parameters to be determined for the spool valve are cylinder diameter ($d_1, d_2$), length ($L_1, L_2$), location and diameter of the port ($L_{cp}, d_e$), gap between plunger and cylinder ($s_{m1}$), maximum displacement of the spool ($z_{1,max}$), and actuator information. In the case of the MV, information such as spring constant ($k_1$), and lengths of the spring under no load condition ($l_{1n}$) and normal operating condition ($l_{1o}$) should be determined because it is a hydraulic actuating by water pressure and a spring may be installed to control them. Thus, to determine them, data on the pressure of the RV ($p_{RV}$) and the pressure of the CV ($p_C$) over time at the time of an accident should be given.

In addition, since the shape of the plunger disk head affect the flow rate due to the displacement of the disk passing through the port, the shape should be determined. The same information will be required for the block valve.

Parameters for the connection between the MV and the BV include pipe configuration, length ($L_{MB}$), diameter ($d_{MB}$), and hydraulic resistance ($K_{MB}$). The same parameters also should be determined for the connection between the BV and the ATV.

### *2.3 Preliminary design sequence of virtual valve*

The most important requirement in determining the geometric parameters of the spool is to provide ECCS flow sufficient for cooling the core following an accident. Based on the reference [6], preliminary sequence of determining the parameters may be as follows:

(1) Under a given pressure boundary condition, the criteria on which the MV should be opened is determined. It is expressed as an opening threshold differential pressure (OTDP) between the RV pressure and the CV pressure. The OTDP of the BV also uses the similar differential pressure between the chamber of BV and the ATV and the value itself may be different. It needs to be optimized through dynamic response analysis.

(2) The maximum displacement of the MV spool is determined by considering the shape of the control port and CV port and spool disk height ($w_{m1}, w_{m2}$). It is to provide a sufficient opening area based on the diameters of the CV port and the control port connected to the MV ($A_C(z_1)., A_e(z_1)$). Generally, circular-shaped port can be used.

(3) The spring constant of the spring installed between the upper disk and the middle retainer of the MV spool is determined. Considering the OTDP value of the main valve and the area of the disk, a pre-compressed state (preload) may be applied under normal operating differential pressure conditions.

(4) The viscous damping coefficient of a spool ($c_1$) is determined from the gap between the moving disk and the stationary cylinder, the fluid viscosity, and the height of the disk. To prevent undesired vibrations, a damping coefficient larger than the critical damping coefficient ($c_{R1}$) must be applied, and this value should be achieved in the detailed design.

(5) The shape, volume ($V_{s1}$), and mass ($m_1$) of the spool are determined by estimating the total length of the MV valve spool ($L_{S1}$), the positions of the disks ($j_{S1t}, j_{S1m}$), etc. For the BV, determine the shape and dimensions of the spool in the same way.

(6) Determine the position and diameter of the control port connecting the upper chamber of the MV and the BV ($j_{MB}, d_{MB}$) based on analysis. They may affect the valve opening time delay and the opening rate.

(7) The overall size of the valve is determined by properly estimating the length of the connection pipe between the two valves, the diameter and length of the pipe connecting the lower chamber of the MV and the lower chamber of the BV.

(8) Determine the diameter of the outlet port of the BV ($d_t$), the shape and length ($L_t$) and hydraulic resistance ($K_t$) of the pipe to the trip valve based on analysis.

The dynamic response is calculated for the configuration determined through the above process, and is iteratively calculated while changing various parameters until a desired response is obtained. The preliminary sequence is for one virtual valve described above and should be changed accordingly when the mechanism, shape, and component of the valve are changed.

## 3. SEMICOM Method

### *3.1 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. Based on the reference [6], the equation of motion for two spools of the MV and the BV are as follows:

$$m_1\ddot{z}_1 + c_1\dot{z}_1 + k_1(z_1 - l_{10}) = F_{1p} + R_{1z} + R_{2z} \tag{1}$$

$$m_B\ddot{z}_B + c_B\dot{z}_B + k_B(z_B + l_{B0}) = F_{Bp} + R_{Bz} \tag{2}$$

where, $m, c, k, z, F, R$ mean mass, damping coefficient, spring constant, displacement, force by pressure difference, force by momentum change, respectively. External forces of those equations can be as follows.

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

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

$$R_{1z} = \rho_1(Q_e\dot{z}_1 + Q_R|v_R|) \tag{5}$$

$$R_{2z} = -\rho_2\left\{A_2L_2\left(\frac{\partial v_c}{\partial t}\right) + v_cA_1\dot{z}_1 - Q_c|v_c| + Q_R|v_R|\right\} \tag{6}$$

For the block valve, they can be obtained in a similar way. Detailed description of the equations can be found in reference [5].

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

The effective area of the disk subject to pressure may vary depending on the geometry, which can be simulated using the control variables of the MARS-KS code. Currently, a constant area is applied, but a variable area will be applied for more detailed design calculation.

### *3.2 MARS-KS modeling*

Figure 2 shows the overall MARS-KS nodalization for the valve system. Five hydrodynamic volumes, including the upper and lower chambers of the MV, the upper chamber of the BV, and the connection tubes, were modeled. And ‘servo valve’ components were applied to three ports whose flow area was changed with spool’s moving. Detailed description of the nodalization can be found in reference [3].

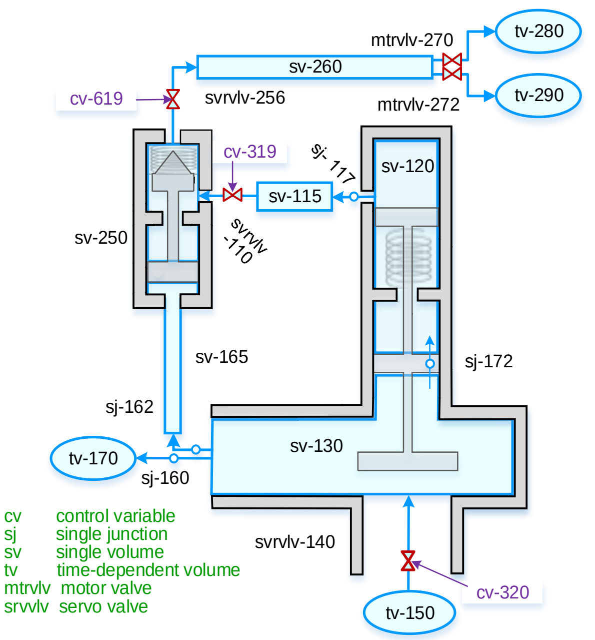


Fig. 2. MARS-KS nodalization of the virtual valve system

## 4. Results and Discussion

The geometric parameters that affect the performance were determined in the sequence above, and the analysis for the base case incorporating them was performed. Specific numbers are non-public information and are not presented here. The pressure boundary condition for dynamic response analysis was the same as the reference [4]. In this analysis, a sensitivity analysis is performed to present results that can be helpful in determining design parameters, in addition to the basic case. Among the various parameters, the sensitivity was analyzed for the spring constant and the viscous damping coefficient of the main valve spool.

### *4.1 Base case*

The basic case response for determining performance parameters was analyzed. Figure 3 shows the pressure response of each part of the system. As shown in the figure, the pressure pulse was found at 30 seconds and 67 seconds. This is a phenomenon related to the closing of the block valve and the opening of the main valve and the block valve as shown in Figure 4. The CV port of the main valve begins to open at 67 seconds and reaches the maximum opening state at 80 seconds.

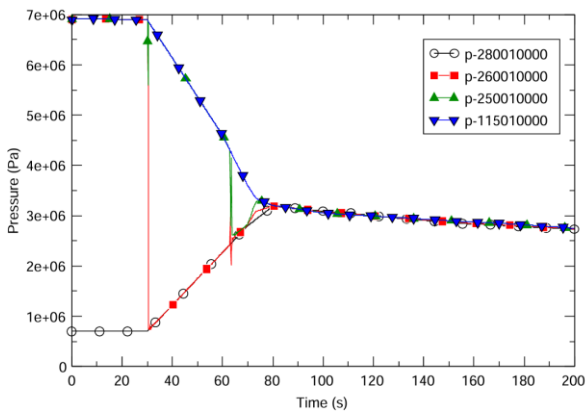


Fig. 3. Calculated pressures in base case

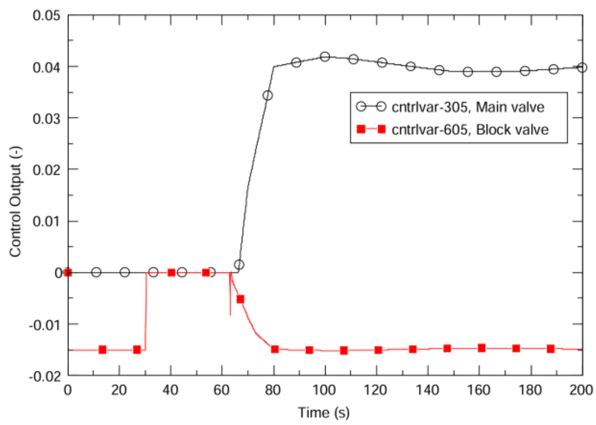


Fig. 4. Calculated displacements of main valve and block valve in base case

### *4.2 Spring constant for the required OTDP*

Sensitivity calculation was performed to see the correlation of the required OTDP and the spring constant of MV for the basic case. Figure 5 shows the correlation between the attempted spring constants and the calculated OTDPs. Approximately linear correlation can be found. Figure 6 compares the displacement behavior of the MV for each of these cases.

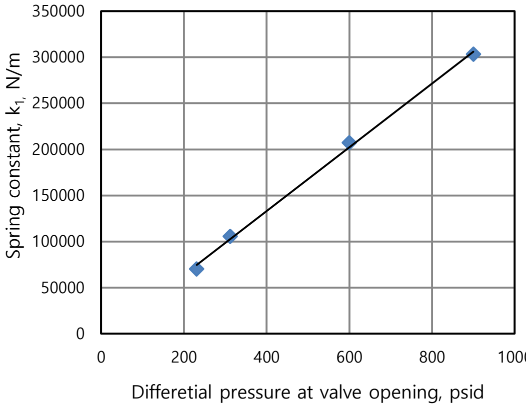


Fig. 5. Calculated OTDP versus spring constant

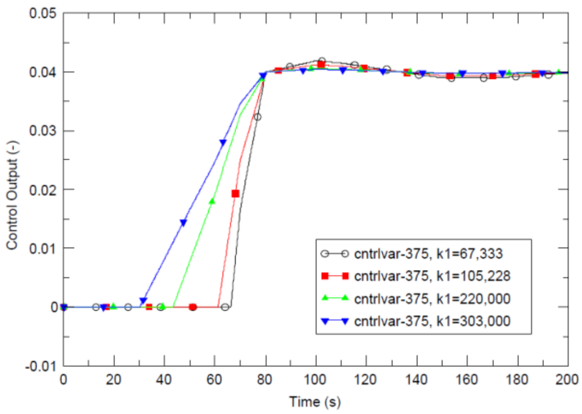


Fig. 6. Comparison of displacement for spring constants

### *4.3 Damping coefficient*

As mentioned earlier, in order to suppress excessive vibration, a damping coefficient greater than the critical damping coefficient determined by the system's natural frequency must be imposed on the system. However, the vibration problem of the spool we are dealing with is a combination of free vibration by spring and mass, and forced vibration by external force by pressure difference and changes in the momentum of the fluid, so we need to know the critical damping coefficient that takes those factors into account. According to the results derived by the authors [5], the critical damping coefficient for this system is not a fixed value, but effect of the pressure difference and the flow characteristics should be considered corrected to the critical damping coefficient of free vibration.

In Figure 7, the MV opening behavior for the range of the damping coefficient for a fixed spring constant was analyzed. The critical damping coefficient for the ideal free vibration ( $2\sqrt{m_1 k_1}$) [6] was 570 N/m-sec, and it can be shown that significant vibration can be generated in the case of a damping coefficient smaller than this value.

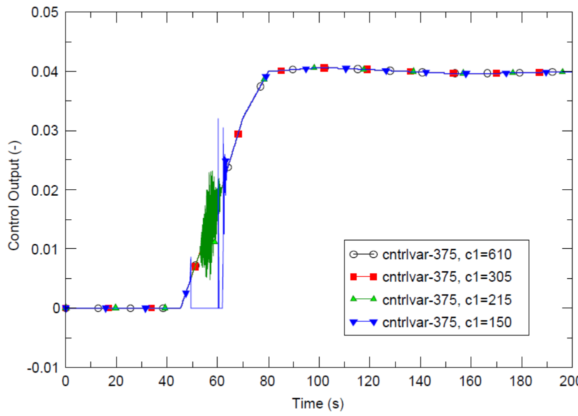


Fig. 7. Comparison of displacement for damping coefficients

Therefore, if the critical damping coefficient of free vibration is applied, it can be shown that additional margin can be obtained. In the actual design, a gap between cylinder and piston head and a piston height to implement this value must be selected.

## 4. Conclusions

Parameters that can affect the performance in the design of PECCS valves were presented, and a process of determining those parameters from a general point of view was proposed based on the research experience so far in the present study. To confirm the validity of the determination the dynamic response was analyzed using the SEMICOM method. In addition, considerations were discussed on the spring constant and viscous damping coefficient of the main valve through the sensitivity analysis. The conclusion is as follows:

1) From the results of dynamic response analysis using SEMICOM for the base case, it was confirmed that the proposed parameters and their decision process were appropriate.
2) The opening threshold differential pressure of the main valve has a linear correlation with the spring constant and it can be predicted by the present method.
3) It was confirmed that stable opening behavior can be achieved when the damping coefficient of the main valve spool was greater than the critical damping coefficient of free vibration excluding the effects of differential pressure and flow momentum.

## ACKNOWLEDGEMENT

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (Ministry of Science and ICT, MSIT) (No. RS-2023-00321928).

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## NOMENCLATURE

**Abbreviation**

| | |
|---|---|
| ATV | actuator trip valve |
| BV | block valve |
| CV | containment vessel |
| MV | main valve |
| OTDP | opening threshold differential pressure |
| PECCS | passive emergency core cooling system |
| RV | reactor vessel |

**Symbol**

| | |
|---|---|
| $A$ | area |
| $c$ | damping coefficient |
| $d$ | diameter |
| $F$ | force on disk by pressure difference |
| g | gravitational acceleration |
| $j$ | distance between disk to disk |
| $K$ | hydraulic resistance |
| $k$ | spring rate |
| $L$ | length of components of valve |
| $l$ | distance from reference position |
| $m$ | mass of spool |
| $p$ | pressure |
| $Q$ | volumetric flow rate |
| $R$ | force acting on spool due to momentum |
| $s$ | clearance between disk and body |
| $z$ | displacement |
| $w$ | height of disk |
| $V$ | volume |
| $v$ | fluid velocity |
| $z$ | displacement |
| $\dot{z}$ | velocity of spool |
| $\ddot{z}$ | acceleration |
| $\rho$ | fluid density |

**Subscript**

| | |
|---|---|
| *1, 2* | chamber 1 and 2 of main valve |
| *B* | block valve |
| *c* | containment port |
| *cp* | distance from center disk to control port |
| *e* | control port |
| *MB* | from main valve to block valve |
| *m1, m2* | disk and retainer of main valve |
| *n* | no load condition |
| *o* | initial positions of spool |
| *p* | force by pressure difference |
| *R* | orifice |
| *rv* | reactor vessel |
| *S1, S2* | spool 1, 2 |
| $S1m$ | from disk 2 to disk 3 of main valve spool |
| $S1t$ | from disk 1 to disk 2 of main valve spool |
| *t* | tube side after block valve |
| *z* | z direction |

**Superscript**

| | |
|---|---|
| * | containment port for main valve |
| ** | containment port for block valve |