Modeling of Dynamic Response of Passive ECCS Valves Using MARS-KS Code in Support of i-SMR

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1. Introduction

Recently, as the development of i-SMR (Innovative small modular reactor) has begun in earnest in Korea, efforts are being made to practically implement several new design concepts of the i-SMR [1]. What stands out in such technology development may be the design of passive emergency core cooling systems (ECCS) and suitable components that meet the design objectives and design requirements of the i-SMR [2]. So far, a combination of hydraulic operated spool valves has been considered to implement the passive characteristics of ECCS valves.

Analysis of dynamic behavior is a key part of spool-type hydraulic design technology. It studies dynamic responses to forces, supply/recovery flow rates, and pressure acting on the piston head [3]. This can be an important part in understanding of hydraulic behavior and how to design the valve to prevent unintended actuation during normal operation, as well as confirming the validity of design performance.

For dynamic behavior analysis, commercial tools and libraries such as Simulation-X [4], MATLAB & Simulink [5], and Modelica [6] have been generally used. In contrast, the analysis using the system thermal-hydraulic code has more advantages and convenience than these commercial tools, however, it has rarely been attempted. It may be because the difficulty from derivation of the governing equations to having to perform complex modeling of implementing and the problem in dealing with the volume change by spool movement. Therefore, for the successful development of such valves, a reliable dynamic behavior analysis tool is required above all else and should be supplemented by comparison with system code analysis in which those difficulties are resolved.

The present study, as part of the overall process to develop the specific design, discusses the development of dynamic behavior analysis model and the related modeling using MARS-KS code [7]. The proposed model is preliminarily applied to the virtual valve having a configuration similar to the reference design. Therefore, the configuration, dimensions, and operating parameters covered in this paper may change as the design proceeds in the future.

2. Governing Equations

The shape of the virtual valve we are concerning is shown in Fig. 1. The valve is composed of a vertical part and a horizontal part, and the vertical part provides pressure for control. The horizontal part opens or closes the port connected to the containment using the pressure difference between the chamber and the containment to supply the ECC water to the reactor. The vertical chamber and the horizontal chamber are separated by the second piston head of the spool passing through them, and the pressure in the upper and lower chambers acts on the piston head to balance the spring force above the retainer.

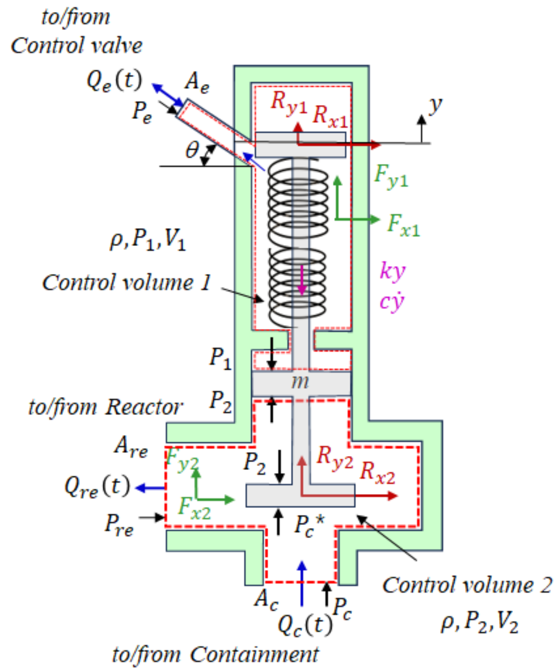

Fig. 1. Configuration of virtual valve and important variables.

The governing equation for the dynamic behavior analysis of the above figure with reference to the text book [3] are continuity equations for each of the two chambers and an equation of motion for the piston passing through the two chambers as follows.

$$continuity\ of\ CV1{:}\quad \frac{dP_1}{dt} = \frac{\beta}{V_1}\left(Q_e - \frac{dV_1}{dt}\right) \qquad (1)$$

$$continuity\ of\ CV2{:}\quad \frac{dP_2}{dt} = \frac{\beta}{V_2}\left(Q_c - \frac{dV_2}{dt}\right) \qquad (2)$$

$$Interface\ condition{:}\quad \frac{dV_2}{dt} = -\frac{dV_1}{dt} \qquad (3)$$

$$\begin{aligned} eq.of motion\ of\ piston{:}\quad & m\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky \\ & = -mg + A_p(P_2 - P_1) \\ & + A_c({P_c}^* - P_2) + R_y \end{aligned} \qquad (4)$$

The meaning of the variables used in these equations can be inferred from Figure 1 and the nomenclature at the end of the paper. ${P_c}^*$ on the right side of this equation means the pressure acting on the bottom of the piston head in the lower chamber, which has a certain value between P_c and P_2 depending on the position of the head.

The force acting on the fluid of each control volume can be obtained from the following Reynold transport theorem.

$$\boldsymbol{F_1} = \frac{\partial}{\partial t}\int_{CV1} \rho\boldsymbol{u}\, dV + \int_{CS1} \rho\boldsymbol{u}(\boldsymbol{u}\cdot\boldsymbol{n})\, dA \qquad (5)$$

$$\boldsymbol{F_2} = \frac{\partial}{\partial t}\int_{CV2} \rho\boldsymbol{u}\, dV + \int_{CS2} \rho\boldsymbol{u}(\boldsymbol{u}\cdot\boldsymbol{n})\, dA \qquad (6)$$

For each control volume, integration is performed in consideration of the flow direction, and the force acting in the y direction is obtained. And it is possible to find the external force applied to the piston that acts in the opposite direction of the force applied to the fluid.

$$\begin{aligned} R_y = -F_y = -\Bigg(& \rho L_v \frac{\partial Q_e}{\partial t} + \rho\frac{{Q_e}^2}{A_e}\sin\theta + \rho L_h \frac{\partial Q_c}{\partial t} \\ & - \rho\frac{{Q_c}^2}{A_c}\Bigg) \end{aligned} \qquad (7)$$

They are the governing equations that must be solved. In hydraulic design, a linearization method is introduced to solve this nonlinear system of ordinary differential equations. In the present study, the pressures and flow rates are obtained using the system code, MARS-KS, without solving the pressure equations (1 and 2). And the equation of motion that cannot be considered by the MARS-KS code is simultaneously solved using control variables within the code run.

3. Modeling Scheme

3.1 Overall features

Fig. 2. shows a nodalization diagram of the valve of interest. The upper and lower chambers are described as one hydraulic volume each, and three time-dependent volumes are added to impose boundary conditions. The flow path areas of the control port (subscript e, valve-110) and the containment port (subscript c, valve-140) change according to the movement of the piston. To take this into account, those ports are described as *servo valve* component provided by MARS-KS code.

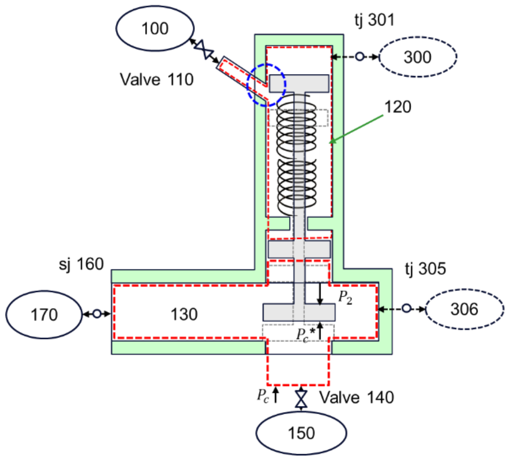

Fig. 2. MARS-KS nodalization of virtual valve

3.2 Consideration of Ports Openings

The fluid density, flow rate, pressure, etc. obtained from the MARS-KS calculation are input into the equation of motion, and the acceleration, speed, and displacement of the piston are solved in an explicit manner using control variables. Here, whether or not the control port and the container port are opened according to the displacement of the piston head and the associated opening area are determined from the separated tables indicating the normalized stem position versus the normalized area.

3.3 Consideration of Volume Change

The volumes of the upper and lower chambers vary according to the movement of the piston, which cannot be considered in the MARS-KS code. In the present study, additional flow path simulating leakage or fill was modeled in each chamber so that the pressure decreased corresponding to the volume increase. (time-dependent junctions, 301 and 305 in Figure 2) as a compensation measure. It was based on that the volume change can be compensated by leakage or fill as follows:

$$\frac{dP}{dt} = \frac{\beta}{V}\left(\bar{Q} - \frac{dV}{dt}\right) \cong \frac{\beta}{V}(\bar{Q} - q_m) \qquad (8)$$

Therefore, the compensating flow rate is determined as follows.

$$q_m = \frac{dV}{dt} = \dot{y}A_p \qquad (9)$$

3.4 Pressure Acting on Bottom Piston Head

When the bottom head of the piston comes into contact with the containment port, the pressure of the containment will act on the bottom surface of the head. If the head moves upward and water flows in from the containment, the pressure acting on the bottom surface of the head can be a certain value between the containment pressure and the pressure of chamber 2. This will have to be determined through specific computational fluid dynamic (CFD) calculations in the future. In this study, it is assumed that the bottom surface pressure changes linearly with the vertical distance from the containment port to the bottom of the head. And if the vertical distance is higher than a certain level, it will be the same as the pressure of chamber 2.

3.5 Gap between Top Piston Head and Cylinder

When the control port is closed by the movement of the uppermost piston head, the control pressure from the control port is blocked, and the upper and lower portions of the head may have different pressures, which may lead to unstable behavior. For this reason, it is important to keep the control port open even at the accident condition. In order to implement it, the minimum value was always read back to 0.1 in the stem position versus opening area table.

3.6 Calculation Algorithm

The overall algorithm of calculation is follows:

1) Specify geometry and the necessary parameters and variables,
2) Get thermal-hydraulic variables such as flow rateand pressure calculated from MARS-KS code,
3) Find the vertical distance from the containment port by the current position of the piston
4) Determine the opening areas of the valves from the predetermined table,
5) Determine the force component (spring, viscous drag, and pressure difference on the piston heads)
6) Determine the external forces caused by the changes of momentum in time and in space
7) Update the acceleration, velocity and displacement of the piston by time integration in order.
8) Using the calculated displacement, determine the volume change and the compensation flow rate
9) Using the changed displacement, determine the opening area of the valve and reflect it in the MARS-KS calculation.

The above algorithm was implemented into the calculation input of MARS-KS by control variables. Calculation is repeated until convergence of the thermal-hydraulic variables is obtained within one time step and then is moved to the next time step in explicit manner.

4. Preliminary Results and Discussion

The modeling scheme described above was applied to the virtual ECCS valve. The main dimensions of the virtual valve are shown in Table 1.

Preliminary calculations were performed to ensure

(1) that the spool of the valve moves to the desired position when the reactor normal condition (NC, reactor pressure of 13.2 MPa, containment pressure of 0.03 MPa) is imposed starting from no load conditions, and
(2) that ECCS is properly started when changed from normal operating conditions to an accident condition (3.5 MPa of reactor and 4.0 MPa of containment).

Table I: Main dimensions of virtual valve

Description		Value (SI unit)
Piston mass	m	0.021 kg
Spring rate	k	82740 N/m
Viscous drag coefficient	c	425 Ns/m
Control port height	e_0	0.006 m
Control port angle	θ	45 deg
Control port pipe area	A_e	1.414×10^{-5} m^2
ECCS pipe diameter and Containment port diameter	D_i	0.05 m
Piston head thickness	t	0.01 m
Initial position of head1	y_0	0.0 m
Length of chamber	L_v, L_h	0.12, 0.12 m
Area of piston	A_p	7.853×10^{-5} m^2

4.1 From No Load to Normal Condition

This calculation simulates a situation in which the pressure of the control port increases first to the normal operating pressure in 0.1 seconds, and then the pressure on the reactor side increases sequentially to 0.2 seconds.

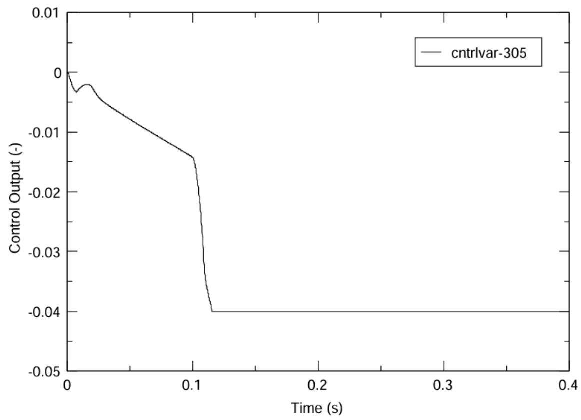

Fig. 3. Displacement of piton head from no load condition to normal condition

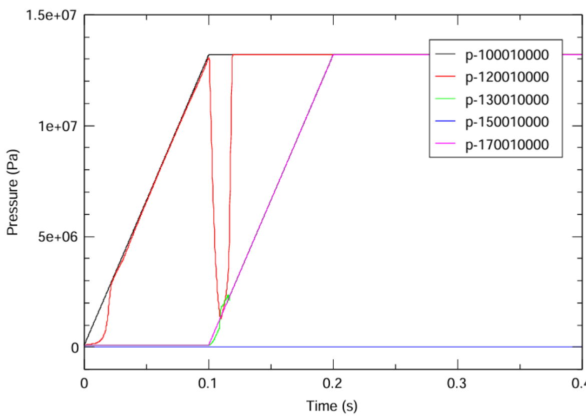

Fig. 4. Pressure responses from no load condition to normal condition

Figure 3 shows a movement of the piton head from no load condition (y=0) to NC, which indicates the piston dropped to the containment port elevation (-0.04 m) in a short time.

Figure 4 shows pressure responses at all volumes. The sequential increase in pressure causes a change in the piston speed, and accordingly, a temporary decrease and increase in the pressure in the upper chamber can be observed.

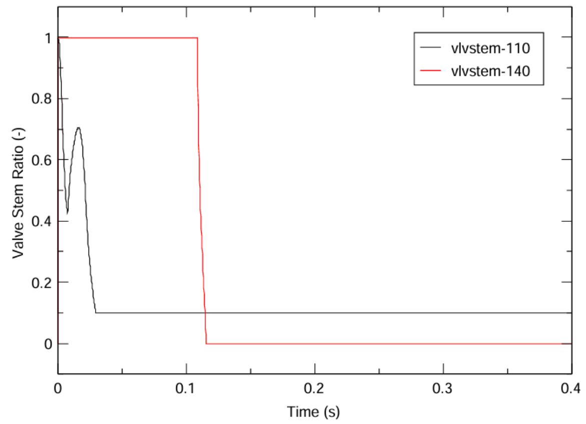

Fig. 5. Valve stem positions Pressures

Figure 5 shows stem positions of the valve for control port and the valve for containment port. It shows that the closing behavior of these valves takes place in a short time, and the control port valve remains open at 10% as intended.

4.2 From Normal Condition to ECCS Actuation

Figure 6 shows the changes of pressure imposed by input at three boundary volumes (control port, reactor and containment port). Expected is, as the reactor pressure decreases and the containment pressure increases, the valve will open and the water from the containment will flow into the reactor. At this time, the control pressure on the control port side can affect the opening time.

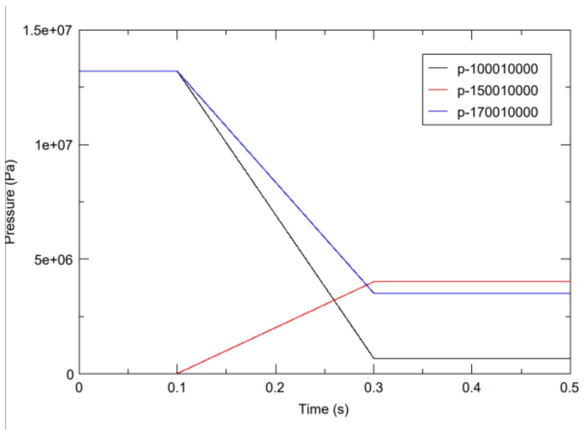

Fig. 6. Pressure changes at three time-dependent volumes

In this calculation, the situation in which the control port pressure and the reactor side pressure decrease from 0.1 seconds to 0.3 seconds, and the containment pressure increases at the same time, is simulated.

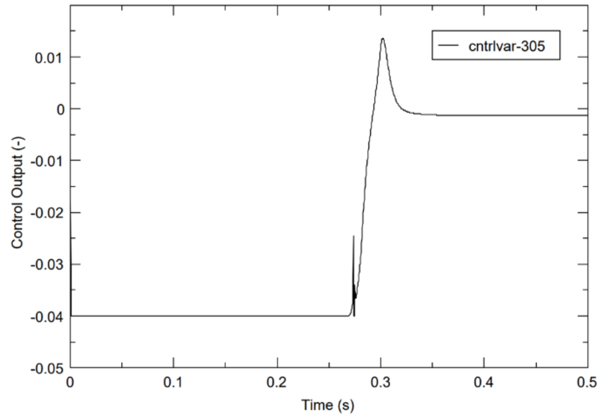

Fig. 7. Response of displacement of piston head

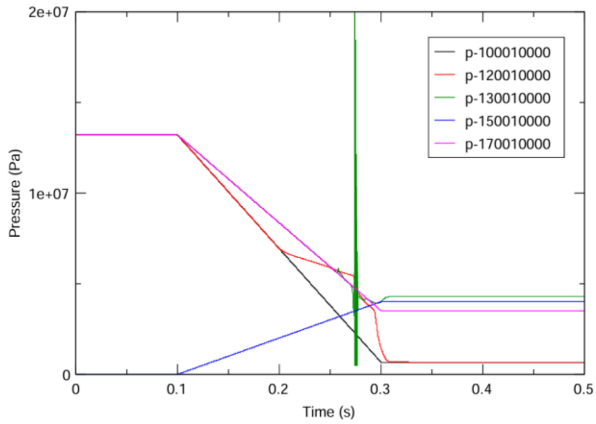

Fig. 8. Response of pressures

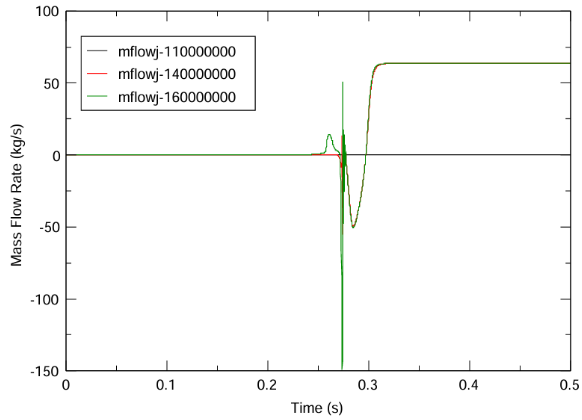

Fig. 9. Response of mass flow rates to reactor

Figures 7, 8 and 9 show dynamic responses in terms of displacement of piston head, pressures at chambers and mass flow rates from containment. From those results, it can be understood that the containment port was opened at a value with a containment pressure slightly lower than 5 MPa, and after a brief reverse flow after opening, it proceeds to a steady state of supplying a flow rate of 50 kg/sec or more to the reactor. The oscillation and peak in the pressure response shown at the moment the containment port begins to open are considered to be numerical oscillations due to a rapid increase and decrease in pressure over a short period of time artificially imposed. It can be overcome in slow transients of actual accidents.

Of course, the results of this dynamic behavior analysis are considered physically valid, but it is thought that experimental verification is necessary to prove the validity of the modeling. However, it is believed that the current modeling can be used to investigate the effect of physical variables, including detailed dimensions of valve components to be determined in the design.

5. Conclusions

A modeling scheme was developed that combined the system code MARS-KS and the explicit solver of the equation of motion using the control variables provided by the code to analyze the dynamic behavior of a passive ECCS valve in the present study. This modeling scheme was applied to a virtual hydraulic operated spool valve equipped with a spring, with two chambers each connected to a containment port and a control port. As conclusions,

(1) As a result of the analysis of the transition where the reactor is depressurized from normal operating conditions to ECCS actuation condition, it was found that physically valid dynamic behavior was predicted.

(2) Experimental validation of the present modeling scheme is necessary, but it is thought that the modeling scheme can be applied to investigate the effect of major variables on the dynamic behavior of valves even in the current state.

ACKNOWLEDGEMENT

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NOMENCLATURES

A	Area
D	Diameter
$\boldsymbol{F}, F$	Force vector and force on fluid
L	Length of chamber
P	Pressure
Q	Volumetric flow rate
R	Reaction force on piston due to momentum change
V, Vol	Volume
c	Viscous drag coefficient of water
e	Control port height
f	force on piston by spring, damping and differential pressure
g	Gravitational acceleration
k	Spring constant or rate
m	Mass of piston
$\boldsymbol{n}$	Unit normal vector
q	Compensating flow rate
t	Time, thickness of head
$\boldsymbol{u}$	Fluid velocity vector
y	Displacement of piston in y direction
	Greeks
β	Bulk modulus of water
η	Normalized distance from the containment port
θ	Angle of control port
ρ	Fluid density
	Subscripts and Superscripts
x, y	Direction in x and y
1	Upper chamber
2	Lower chamber
c	Containment port, due to damping
e	Control port
i	Injection pipe
m	Compensating flow
n	n-th time step
p	Due to pressure difference, piston
v, h	Vertical and horizontal
$*$	Index for pressure acting on bottom surface of the bottom piston head