Application of MATLAB to Predict Dynamic Behavior of PECCS Valves of i-SMR

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1. Introduction

Design of the valve of the Passive Emergency Core Cooling System (PECCS) of Innovative Small Modular Reactos (i-SMR) shall be able to accommodate the various design specifications required by the safety analysis of the plant, such as opening differential pressure thresholds, dynamic characteristics of opening and closing, etc. [1]. Authors have been developing the SEMICOM (Solution of Equation of Motion Implemented by Control variables of MARS-KS code) method to analyze the dynamic behavior of the valve [2]. The SEMICOM method determines the displacement of valve and its opening area using the values such as pressure and flow calculated by the MARS-KS code [3] and then feeds it back to the input of the MARS-KS calculation. In this method, however, the change of volume of the chamber in the valve during its movement has not been considered due to the use of the system thermal-hydraulic code. This method has no problem in application whose the volume change is not serious or the valve spool is not moving at a large speed. However, it is necessary to consider the effects of volume changes to ensure the reliability of dynamic behavior analysis.

To address this problem, a hydraulic analysis that can consider the equation of motion of the valve spool with the volume change of the associated chamber is develped using MATLAB [4]. And it is compared with the SEMICOM calculation result. To do this, the calculation is performed on the model proposed preliminarily by the valve supplier [5].

2. Modeling

A valve model proposed by the valve supplier is proprietary information. But for the understanding, it can be mentioned that the valve consists of a main valve (MV) that passively supplies water from the CV to the RPV, a block valve (BV) that affects the opening of the main valve, a trip valve connecting the block valve and the CV, and connection flow path. Each valve has a retainer, which is connected to the spool disk by a spring to control the movement of the spool. Detailed data of this valve and an analysis performed using the SEMICOM method in the reference [2].

2.1 Governing Equations

Fig. 1 shows an schematic illustration of the valve configuration and notation for the MATLAB modeling. In the configuration, the valve is composed of two spools within the valve body having one or two disks, an armature, and a spring. The opening area of the MV and BV are determined by the positions of the disks.

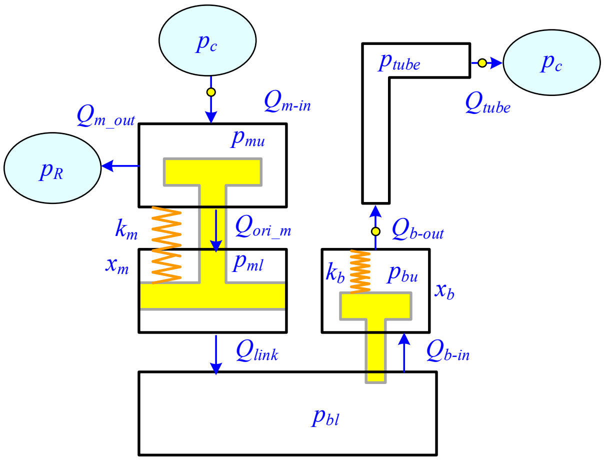

Fig. 1 valve configuration and noding scheme

Five volumes to calculate the fluid pressure and seven paths to calculate the flow rate between volumes are shown in the figure.

The pressure rise rate equation for volume i can be as follows

$$\frac{dp_i}{dt} = \frac{\beta}{V_i}\left(Q_{i-in} - Q_{i-out} - \frac{dV_i}{dt}\right) \qquad (1)$$

where p, t, β, V, and Q are pressure, time, bulk modulus of fluid, and volumetric flow rate, respectively. This equation has a term accounting the change of volume. Totally five equations can be obtained based on Fig. 1.

The orifice equation for the path connecting the volume i and volume j can be as follows:

$$Q_{i-j} = C_d A_{i-j}\sqrt{2\left|p_i - p_j\right|/\rho} \cdot sign(p_i - p_j) \qquad (2)$$

where C_d, A_{i-j} and ρ mean discharge coefficient, path flow area and fluid density. The symbol *sign* returns +1 or -1 depending on whether the value of the variable in parentheses is positive or negative. Totally, seven orifice equations can be obtained including the paths connecting chambers to the CV and RPV.

The positions of the disks can be determined by the equation of motion of the spools as follows:

$$m_m \ddot{x}_m + c_m \dot{x}_m + k_m x_m = F_{p\_m} + F_{m\_m} + F_{res\_m} \quad (3)$$

$$m_b \ddot{x}_b + c_b \dot{x}_b + k_b x_b = F_{p\_b} + F_{m\_b} + F_{res\_b} \quad (4)$$

where, m, c, k, x, F_p, F_m and F_{res} mean mass, damping coefficient, spring constant, external force by pressure difference over the disks, external force by momentum change in each chamber, and external force to restore external force applied to the spool when the displacement of the spool exceeds the upper and lower limits of movement and comes into contact with the retainer. Subscripts m and b mean MV and BV, respectively.

The force by pressure is determined by considering the area in which the pressure acts. The force due to the momentum change is obtained by Reynolds transport theorem and is represented by the force due to the steady-state flow and the force due to the time change of momentum within the control volume [2].

2.2 MATLAB Solution

The equations (1) to (4) and additional equations for the external forces leads to a system of time-dependent nonlinear ordinary differential equations (ODE). By converting the second-order equation of motion in terms of spool displacement into the equation in terms of spool velocity and expressing the first order differentiation in those equations, which leads to nine equations with nine unknowns as follows:

$$\boldsymbol{x} = \{x_b, v_b, x_m, v_m, p_{bu}, p_{bl}, p_{mu}, p_{ml} p_{tube},\} \quad (5)$$

$$\boldsymbol{dx/dt} = \boldsymbol{f} = \{f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8, f_9\} \quad (6)$$

$$\begin{aligned}
f_1 &= v_b \\
f_2 &= (F_{net-b} - c_b v_b + k_b x_b)/m_b \\
f_3 &= v_m \\
f_4 &= (F_{net-m} - c_m v_m + k_m x_m)/m_m \\
f_5 &= \beta/V_{bu}\left(Q_{b_{in}} - Q_{b_{out}} + A_{de} v_b\right) \\
f_6 &= \beta/V_{bl}\left\{Q_{link} - Q_{b_{in}} - (A_1 v_m + A_{de} v_b)\right\} \\
f_7 &= \beta/V_{mu}\left(Q_{m_{in}} - Q_{M_{out}} - Q_{ori-m} + A_{Q1} v_m\right) \\
f_8 &= \beta/V_{ml}\left\{Q_{ori-m} - Q_{link} - (A_{Q1} - A_1) v_m\right\}, \\
f_9 &= \beta/V_{Tube}\left(Q_{b-out} - Q_{trip}\right)
\end{aligned} \quad (7)$$

This format is organized to use *ode15s* solver in MATLAB. In the method, the ODE solved implicitely using Newton Raphson method as follows:

$$\boldsymbol{x}_{n+1}^{k+1} = \boldsymbol{x}_{n+1}^{k} - \left[\boldsymbol{I} - h \cdot \boldsymbol{J}(x_{n+1}^{k}, t_{n+1})\right]^{-1} \cdot \left[\boldsymbol{x}_{n+1}^{k} - \boldsymbol{x}_{n}^{k} - h \cdot \boldsymbol{f}(x_{n+1}^{k}, t_{n+1})\right] \quad (8)$$

where $\boldsymbol{I}$, h , and $\boldsymbol{J}$ mean identity matric, time step size, and Jacobian matrix. Subscript *n, m+1* and *k* and *k+1* mean time level and interation level, respectively. Jacobian matrix can be defined as follows:

$$\boldsymbol{J} = \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}} = \begin{bmatrix} \partial f_1/\partial x_1 & \partial f_1/\partial x_2 & \cdots & \partial f_1/\partial x_9 \\ \partial f_2/\partial x_1 & \partial f_2/\partial x_2 & \cdots & \partial f_2/\partial x_9 \\ \cdots & \cdots & \cdots & \cdots \\ \partial f_9/\partial x_1 & \partial f_9/\partial x_2 & \cdots & \partial f_9/\partial x_9 \end{bmatrix} \quad (9)$$

In this equation, the expressions for the flow rates can be made as a function of pressure with reference to equation (2). Expressions for the forces can be found in the literature [2].

Pressure over time of CV and PRV was imposed as the pressure boundary conditions required for hydraulic calculations, as in literature [2].

Upper and lower limits of each spool are given to restrict the movement of them as boundary conditions necessary for solving the equation of motion.

3. Results and Discussions

3.1 Basic Dynamic Response

Figures 2, 3, and 4 show the result of MATLAB calculation: displacements of MV and BV, pressures at the chamberes, and flow rates at the pathes, respectively.

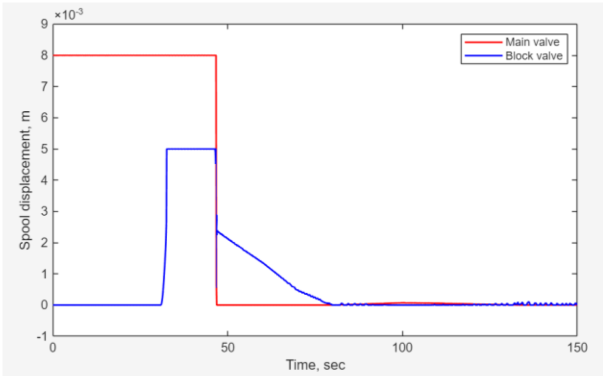

Fig. 2 Displacements of MV spool and BV spool

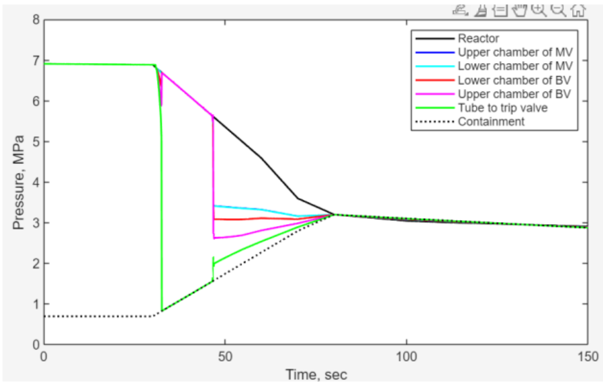

Fig. 3 Pressure responses at all chambers

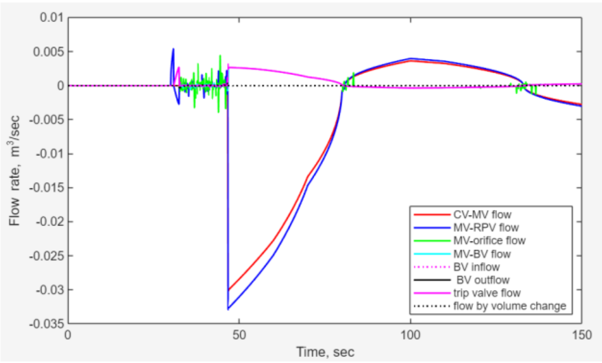

Fig. 4 Flow rates at all pathes

As shown in those figures, pressure response and flow behaviors as well as valve motion were successfully calculated in a stable manner. Details of the MATLAB calculation is discussed in the next section.

3.2 Comparison with SEMICOM

In order to compare the two methods, the geometric and hydraulic characteristics must be the same. However, there is differences in the noding scheme between SEMICOM and MATLAB. And the loss coefficient *k* is used in SEMICOM input, whereas the flow coefficient C_d in MATLAB. Thus, the adjustment of hydraulic parameters was attempted to be as close as possible using the following equations:

$$C_d = \{k + (A_c/A_2)^2 - (A_c/A_1)^2\}^{-1/2} \quad (10)$$

where, A is flow area and subscript *1, 2,* and *c* mean upstream, downstream and connecting junction, respectively.

The values of spring constant, damping coefficient and mass of spool of the MV and BV were preliminarily selected and identical both calculations by SEMICOM and MATLAB, as follows:

$$m_m = 0.1\ kg, c_m = 0.254\ N/\mathrm{m}/sec, k_m = 300{,}000\ N/m.$$

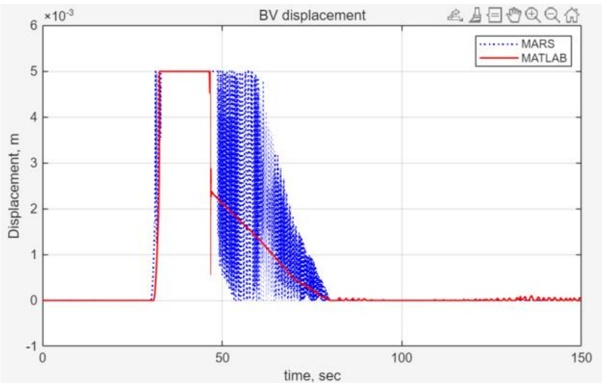

Fig. 5 Comparison of BV displacement

Figures 5 and 6, show comparisions of the BV displacement, the pressures at MV upper chamber, BV upper chamber, and tube to trip valve, respectively. The overall trend can be said to be similar. However, there are noticeable deviations in SEMICOM from the MATLAB results

(1) significant oscillation in BV opening phase,
(2) oscillation in pressure at BV chambers.

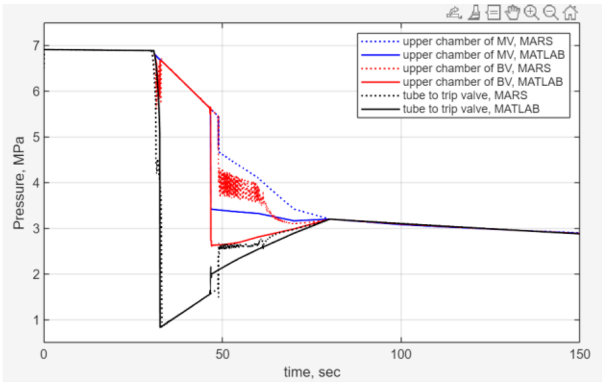

Fig. 6 Comparison of pressure at MV upper chamber

It can be estimated that the cause of the difference item (1) is due to the difference between the SEMICOM model using the MARS-KS code and the MATLAB using the pressure rise rate equation. That is, it is the effect of the chamber volume change rate on the pressure change rate.

Figure 7 compares the pressure force acting and the spring force on the BV spool in two models. In the case of MATLAB considering the volume change, the pressure and pressure force have decreased to a stable level as the volume of the BV chamber has increased, whereas in the SEMICOM model, the phenomenon that the pressure decreases and then increases to a level without volume change occurs repeatedly. This effect results in violent vibration of the spring force and the spool, which lasts until the pressure force reaches zero.

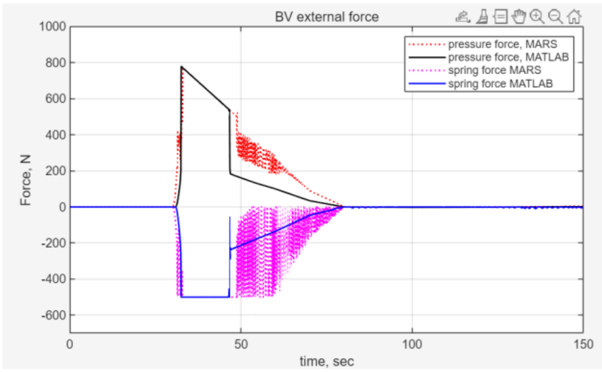

Fig. 7 Comparison of external forces on BV

To confirm this concern, an additional calculation was performed on the case where the term for the rate of volume change was deleted in the process of solving the pressure rise rate equation in the MATLAB model. The results are presented in Figure 8 compared to the original MATLAB calculation results. As shown in the figure, if the rate of volume change was not considered, significant oscillation was predicted as the BV was opened. This, of course, does not explain the entire difference in predictive behavior between MATLAB and SEMICOM, but it can be confirmed that it is one cause for the oscillations in the early stages of BV opening.

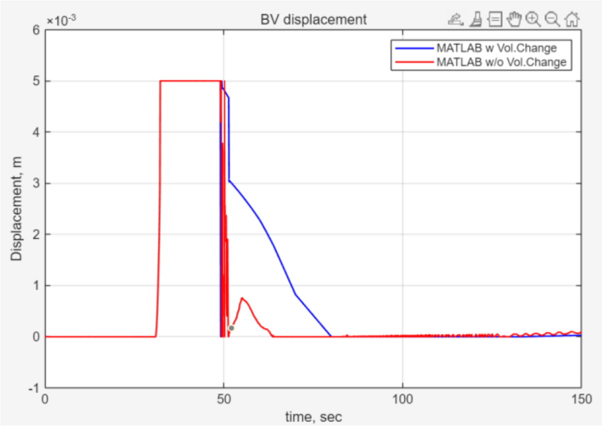

Fig. 8 Comparison of BV displacement for consideration of volume change rate

3. Conclusions

In order to predict the dynamic behavior of the PECCS valve, a MATLAB model was developed. This method solves the pressure rise rate equations for each chamber of the valve, where the effect of the volume change rate was considered, which has not been considered in the existing SEMICOM method using the MARS-KS code. The MATLAB analysis result was compared with SEMICOM results. The following conclusions can be obtained:

(1) For the valve configuration presented by the valve supplier, the present MATLAB model has been successfully developed, which provided reasonable and stable behavior of the valve.

(2) Given the difference in hydraulic characteristics between MATLAB and SEMICOM, the behavior predicted by MATLAB model, in a large sense, was similar to the one calculated by SEMICOM.

(3) The most prominent difference was the oscillation of block valve during the opening phase in SEMICOM and it may be due to absenc of the volume change rate modeling. Thus, it may request the improvement of SEMICOM model to consider additional junctions to consider the flow rate due to volume change rate.

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