Modeling and Validation of Long Multi-Stage Orifice (MSO) Performance for Passive ECCS Valves

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1. Introduction

In order to satisfy the timing and duration of opening and closing of the ECCS (Emergency Core Cooling System) valve which has been required by the safety analysis of the i-SMR (Innovative Small Modular Reactors) design, it is necessary to build an appropriate differential pressure between the associated chambers which is to balance the designed spring forces [1]. It also should be confirmed for the structural integrity that a stable response of full opening and closing of the valve upon the signal can be achieved. To realize those features, the orifice may be introduced [2], which imposes an appropriate differential pressure while connecting the separated chambers. An example is shown in Figure 1. Since those orifices are perforated through a fixed part of the valve, they are regarded as thick or long orifices, in general sense. A multi-stage orifice (MSO) in which the area of the orifice hole changes in stepwise manner may also be considered to provide more sophisticated control and to prevent cavitation within the orifice. However, most of the current research results are for thin orifices, so it is difficult to apply them to this problem [3, 4]

Recently, Gao et al. derived the theoretical discharge coefficient for 2-stage orifice corresponding to relatively thick orifice and conducted some experiments [5]. In the present study, a modeling scheme to represent 3-stage thick orifice is discussed, based on Gao's theory [5]. The scheme will be adopted in the current MATLAB-based program dynamic behavior analysis [6].

2. Modeling of Multi-Stage Orifice (MSO)

The flow rate supplied by Passive ECCS to the reactor vessel is determined by the area of the outlet port and the pressure difference across the outlet port, which is determined by the displacement of the spool of the valve. Since the displacement of the spool is determined by the differential pressure between chambers and the spring constant, it is important to accurately calculate the differential pressure between chambers. The present study is to present a model that calculates the equivalent discharge coefficient addressing the relationship between the differential pressure and flow rates imposed on a multi-stage orifice.

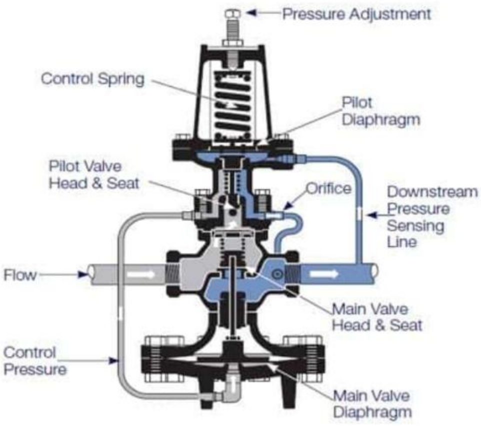
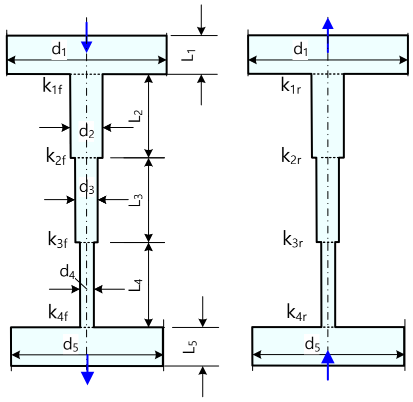


Fig. 1. Valve with orifice



a) forward flow
b) reverse flow

Fig. 2. Configuration of long multi-stage orifice

Figure 2 shows the three-stage orifice of interest in the present study. Due to the nature of the PECCS valve, there may be reverse flow flowing from the CV (Containment Vessel) to the RPV (Reactor Pressure Vessel), thus, modeling of the reverse flow is also required. In general, the orifice equation for a thin plate orifice is as follows.

$$Q = C_d A_0 \sqrt{2\Delta p/\rho} \qquad (1)$$

where, Q, C_d, A_0 Δp, and ρ are volumetric flow rate, discharge coefficient, orifice hole area, differential pressure, and density, respectively. This equation was obtained under the condition that the area of the pipe at upstream and downstream of the orifice is the same in the Bernoulli equation. However, the area of the inlet chamber and the outlet chamber is different, and for a long tube orifice, the discharge coefficient must be defined in consideration of the entrance loss, pipe friction loss, and exit loss. For forward flow orifice shaped as shown in Figure 2, the Bernoulli equation for flow path 1-4 is as follows

$$\frac{p_i}{\rho g}+\frac{{u_i}^2}{2g}=\frac{p_{i+1}}{\rho g}+\frac{{u_{i+1}}^2}{2g}+\xi_1\frac{{u_{i+1}}^2}{2g} \qquad (2)$$

$$\xi_i = k_{if} \ + f_{i+1}\frac{L_{i+1}}{d_{i+1}}, i = 1,2,3 \qquad (3)$$

where u, ξ, k, f, L, and d mean velocity, total loss coefficient, friction factor, length, and diameter, respectively. The stage of the orifice is expressed the subscript *i*. The flow path 4-5 is a sudden expanded one, thus, the momentum conservation equation is applied according to the reference [7].

$$\rho A_5 u_5(u_5-u_4)=(p_4-p_5)A_5 \qquad (4)$$

Continuity equation of each stage is as follows:

$$Q = A_j u_j \qquad (5)$$

Pressure drop of each stage of orifice is as follows:

$$\Delta p_{i,i+1} = \begin{cases} \frac{\rho}{2}\{(1+\xi_i){u_{i+1}}^2-{u_i}^2\}, i = 1,2,3 \\ \rho u_{i+1}(u_{i+1}-u_i), i = 4 \end{cases} \qquad (6)$$

Substituting those equations into Eq (1) leads to an equivalent discharge coefficient

$$C_{d,eq} = \frac{Q}{A_0\sqrt{2(\Delta p_{1,2}+\Delta p_{2,3}+\Delta p_{3,4}+\Delta p_{4,5})/\rho}} \qquad (7)$$

The equation implies that the equivalent discharge coefficient can be determined by geometric configurations and loss coefficients from minor loss and pipe friction. The minor loss coefficient can be found in reference [8]. The friction factor of pipe wall in the laminar flow region is as follows:

$$f_L = 64/Re_i, \qquad Re < 2000 \qquad (8)$$

where Re_i is defined as follows:

$$Re_i = u_i d_i/v \qquad (9)$$

where is v dynamic viscosity.

In the turbulent region ($Re_i > 4000$), the Blasius equation and Haaland [9] equation is used for smooth tubes and for rough tubes, respectively.

$$f_T = \begin{cases} 0.3164\, {Re_i}^{-0.25} \\ \left[-1.8\log_{10}\left(\frac{\varepsilon/D}{3.7^{1.11}}+\frac{6.9}{Re_i}\right)\right]^{-2}, \end{cases} \qquad (10)$$

In the transition region, their interpolation is used.

$$f_{L-T} = f_L + \theta(f_T - f_L), \quad \theta = (Re-2000)/2000 \qquad (11)$$

In the case of reverse flow, Eq (11) can be continuously applied considering the pressure drop of each stage as follows:

$$\Delta p_{i+1,i} = \begin{cases} \frac{\rho}{2}\{(1+\xi_i){u_i}^2-{u_{i+1}}^2\}, i = 4 \\ \rho u_{i+1}(u_{i+1}-u_i), i = 3,2,1 \end{cases} \qquad (12)$$

These equations can also be easily extended to two-stage orifice and single-stage orifice.

3. Performance of MSO

The modeling scheme described in the previous section was implemented into MATLAB program. From the calculation result, the behavior of the differential pressure and the equivalent discharge coefficient by the change in flow rate was investigated. The orifice used in the performance calculation is a virtual three-stage orifice with a diameter of 0.2 m and 0.17 m of the inlet and outlet chambers, and a diameter of each orifice stage of 0.01, 0.007, 0.005 m and a length of 0.04, 0.048 and 0.034 m, respectively. Roughness of the orifices was selected as 10-4 m, thus, the Haaland equation was applied in the calculation.

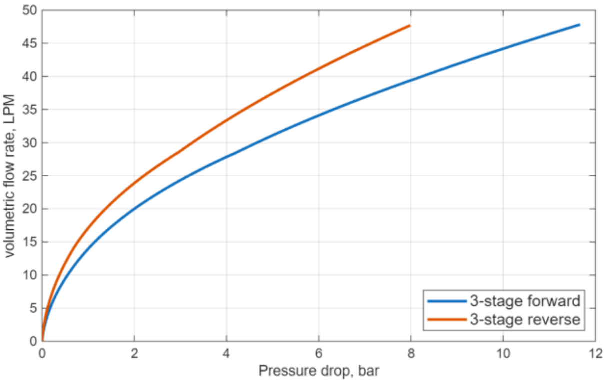


Fig. 3. Calculated pressure drop versus flow rate

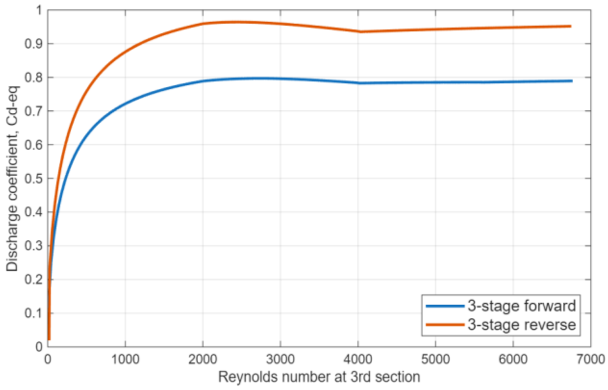


Fig. 4. Calculated discharge coefficient versus flow rate

Figures 3 and 4 show the behavior of differential pressure in the calculated flow rate range and the trend of the equivalent discharge coefficient with respect to Reynolds number, for forwarding flow and for reversing flow, respectively. As shown in the figure, it can be found that the equivalent discharge coefficient increases with the Reynolds number and then decreases slightly in the transition region and has almost a constant value in the turbulent region.

In the case of reversing flow, as expected, a smaller differential pressure can be obtained than in the forwarding flow even at the same flow rate. This is because in the case of reverse flow, the loss coefficient becomes smaller than in the case of forward flow as the flow path gradually expands (Fig. 5). As a result, it can be found that the discharge coefficient under the reversing flow condition is larger than that of the forwarding flow condition.

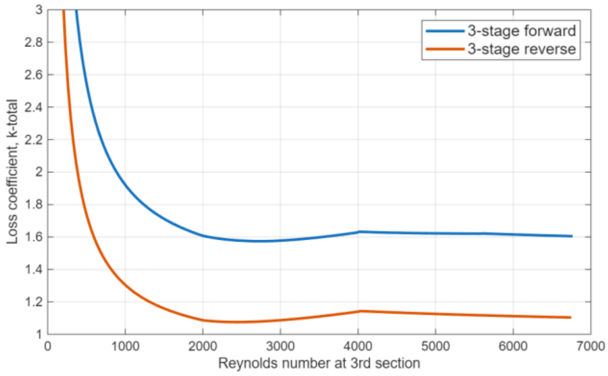


Fig. 5. Calculated loss coefficients versus Reynolds numebr

The calculation was performed on the assumption of a two-stage orifice and a one-stage orifice having the same length as the three-stage orifice. Figures 6 and 7 show the comparisons of the differential pressure behavior and discharge coefficient behavior of the three orifices. From this result, it can be found that the differential pressure produced by the three-stage orifice under the same flow rate condition is smaller than that of the two-stage orifice and has a larger discharge coefficient.

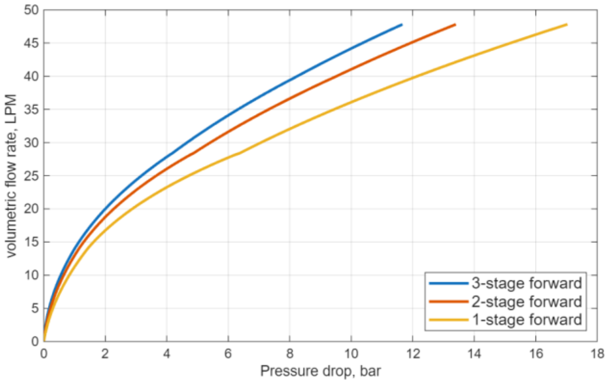


Fig. 6. Comparison of pressure drop behavior for three cases

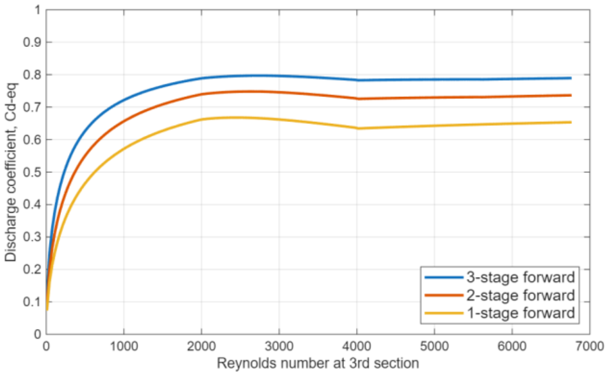


Fig. 7. Comparison of discharge coefficients for three cases

4. Validation

To confirm whether the equivalent discharge coefficient of the three-stage orifice applied in the present study is appropriate, the experiment presented in Gao's paper [5] was simulated. Figure 8 shows the configurations of the two-stage and one-stage orifice used in the experiment. Detailed dimensions can be found in the literature [5]

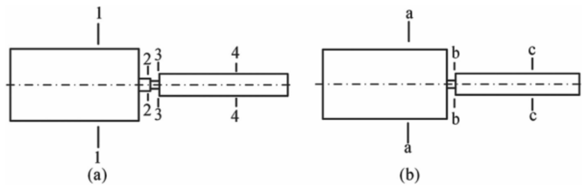


Fig. 8. Configuration of orifices in the experiment [5]

Figures 9 and 10 show the results calculated with the MATLAB code compared with the experimental data.

As shown in the figure, the flow-differential pressure characteristics agree well with the experimental data in both the two-stage orifice and the single-stage orifice. In the case of the equivalent discharge coefficient, it can be shown that the experimental data are properly predicted as a whole. In order to predict the equivalent discharge coefficient more accurately, the sensitivity analysis to the uncertainty of the minor loss coefficient may be needed.

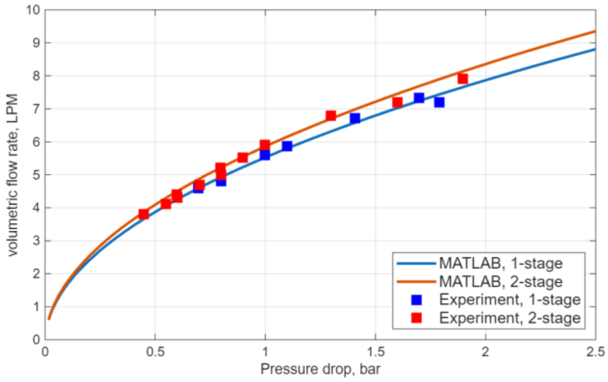


Fig. 9 Comparison of predicted Δp-Q with experiment data

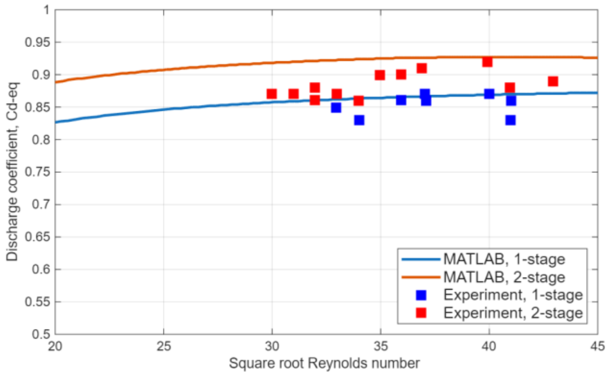


Fig. 10 Comparison of predicted Cd-Re with experiment data

5. Conclusions

The present study discussed the modeling scheme for long-hole multi-stage orifice that is considered in PECCS valve design. Based on Gao's theory, the equivalent discharge coefficients in the forward and reverse directions were evaluated for the three-stage orifice. In addition, the validity of the prediction was confirmed by comparing it with Gao's experimental data. The obtained conclusion is as follows.

1) The proposed equivalent discharge coefficient modeling scheme shows good agreement compared to Gao's experimental data, so it can be applied to the performance evaluation of multi-stage orifice.
2) Based on the calculation results of the virtual three-stage orifice, the forward and reverse flows show different discharge coefficient characteristics, and the case of reverse flow shows a larger discharge coefficient due to flow path expansion.
3) In order to improve the prediction accuracy, it is necessary to evaluate the uncertainty of minor loss coefficient.

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