Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Modeling of Swing Check Valve in Support of Prediction of Passive Safety Systems Performance

Young Seok Bang [a*], Ju Yeop Park [a], Yong Seog Choi [a]
[a]*Korea Institute of Nuclear Safety, 62 Kwahak-ro, Yuseong, Daejeon, Korea*

1. Introduction

Swing check valves are widely used in many systems of nuclear power plants to form flow in a predetermined direction and prevent backflow. The importance of check valves is still recognized not only in the design of the existing active safety system but also in the performance of the passive safety system which has recently been in the spotlight. For example, SMART1000 Standard Design [1], which is under review, has a Passive Safety Injection System (PSIS) with multiple check valves installed. The valves play a key role in injecting water from the Core Makeup Tanks (CMT) and the Safety Injection Tanks (SIT) into the core while preventing backflow between the PSIS and the reactor and between the SIT and the CMT following an accident.

The swing check valve is operated by the pressure difference between upstream and downstream of the valve, the inertia of the swing disk, thus, the flow rate and pressure loss across the valve are determined by the opening angle of the disk. Also, in the performance evaluation of the passive safety system, the opening time and closing time, and the characteristics of the water hammer phenomenon should be accurately evaluated including their transient behaviors considering the transient angle of the disk.

The present study aims to discuss an accurate and reliable swing check valve model which can be used in regulatory supporting calculation on passive safety system. To this purpose, the built-in model in MARS-KS code [2] and the improved model [3] are examined through the calculation of the experiment of swing check valve closure [3].

2. Mathematical Models

In this study, calculations are conducted using MARS-KS code. In the code's algorithm, the calculated pressures are used to determine the disk angle, and then the flow area, which is used to determine the pressure loss and then pressure by the change of flow area, the process is repeated. Accordingly, disk angle is one of the key parameters in the check valve behavior.

2.1 Built-in model of swing check valve of MARS-KS

Angle of the disk is obtained by solving torque inertia equation for swing check valve in RELAP5 [4] code is as follows:

$$I\ddot{\theta} = \Delta p_F A_d L + \Delta p A_P L - MgLBsin\theta \qquad (1)$$

Where, I means the moment of inertia of disk, θ the angle of disk from the vertical axis, Δp_F the cracking pressure initiating the disk motion, A_d the disk area, L the length of arm, Δp the pressure difference between the upstream and the downstream of swing disk, A_P the projected area, M the mass of disk, and B buoyance factor respectively.

Originally, MARS-KS code had the same model as RELAP5. The MARS-KS model, however, was changed to improve some deficiencies based on the study [5]. The changed governing equation is as follows:

$$I\ddot{\theta} = \Delta p_F A_d L + T_p + T_v - C_d D^5 \dot{\theta}|\dot{\theta}| - (M_{arm} + M_{disk})gLBsin\theta \qquad (2)$$

The equation has a pressure difference torque term, which was revised using the flow velocity as follows:

$$T_p = \Delta p A_P L = (K_b \theta)^{-3} \rho v^2 A_P L \qquad (3)$$

Torque terms due to flow impingement, T_v and damping torque term, $C_d D^5 \dot{\theta}|\dot{\theta}|$ were newly implemented in the equation. Torque due to the weight of the arm of the swing disk was also considered. The projected area, A_P, is obtained through a complex integration process of finding the area formed by the intersection of the circle of the pipe and the ellipse whose center and aspect ratio change depending on the disk angle. Details of each term was described in the paper [5].

Those improvements reflect the results of various studies so far [3, 6, 7], but there are some parts unclear in determining the various coefficients, and the sufficient validation based on experiment data has not been made.

2.2 Improved model

A swing check valve model supported by the experiment data has been proposed in reference [4]. Fig. 1 shows a concept of the improved model.

The model is actually similar to the current MARS-KS model even though there are some differences in mathematical expression. The governing equation is as follows:

$$(I_m + I_F)\ddot{\theta} = T_{HS} + T_{HR} + T_{FK} - M_{tot} gLsin\theta \qquad (4)$$

As shown, the inertia term due to added fluid mass nearby the swing disk, I_F, is introduced. Two hydraulic torques, stationary one, T_{HS}, and rotating one, T_{HR}, are the same as the pressure difference torque and damping torque of the MARS-KS, respectively. They are as follows:

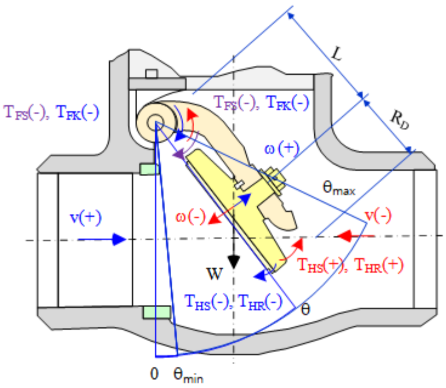

Fig. 1. Swing check valve model

$$T_{HS} = C_{HS}\rho\frac{{v_R}^2}{2}A_dL = \frac{1}{2}C_{HS}\rho A_dLv_R|v_R| \qquad (5)$$

$$T_{HR} = C_{HR}\rho\frac{1}{2}L\dot{\theta}|L\dot{\theta}|A_dL \qquad (6)$$

The coefficients of the equations, C_{HS}, C_{HR} were provided as a function of angle based on the measured data [3]. In the present study, however, both coefficients were assumed as constants averaged over the angle for simplicity.

Based on the result of the integration process to implement into MARS-KS built-in model, the projected area can be regarded as a linearly varying variable with the disk angle between the minimum and the maximum.

Cracking pressure in the MARS-KS model was interpreted by frictional torques of at the hinge at stationary state and at kinetic state, respectively. They are expressed as follows [3]:

$$T_{FK} = T_{FS} - T_{FK} = \pm 0.018 \mp 0.003\dot{\theta} \qquad (7)$$

The sign of each term of the right-hand side is determined by the direction of disk movement.

Using the angular acceleration, $\ddot{\theta}$, calculated by the method described above, the angular velocity, ω, and angle of the disk, θ, are calculated as follows.

$$\omega^n = \dot{\theta}^n = \dot{\theta}^{n-1} + \ddot{\theta}^n\Delta t \qquad (8)$$

$$\theta^n = \theta^{n-1} + 0.5(\omega^{n-1} + \omega^n) \qquad (9)$$

In this study, calculations were made using the built-in model of the MARS-KS code represented by Eq(1) and the model represented by Eq(4).

3. Experiment

An experiment of swing check valve closing was reported in the reference [3]. The test loop was shown in Fig.2. The swing check valve is installed in the middle of the loop. The main specifications of the check valve are in Table 1.

Table 1. Specifications of the check valve in the test

Parameter	Value
valve disk diameter, R_D	74.93 mm
submerged weight in water, M_{tot}	3.65 N
length of arm, L	0.055 m
moment of inertia of rotating parts, I_m	0.0018 Nm-s^2
moment of inertia of added mass, I_F	0.0007 Nm-s^2
minimum angle, θ_{min}	14.8 deg
maximum angle, θ_{max}	14.8 +70 deg

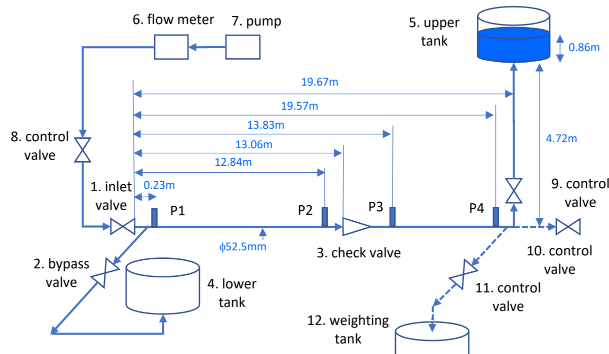

Fig. 2. Test loop for swing check valve test

In the experiment, water was discharged at a constant velocity (1.93 m/sec) through a pump, the average pressure at P3 location was 61.02 kPa(g) during the steady state. At a certain time, the inlet valve was closed and the closing behavior of the check valve, i e, angle of the disk, pressures before and after the valve were measured, respectively.

4. Modeling

Fig.3 shows a MARS-KS nodalization of the test loop. Main part of the loop including the upper tank was modeled. Volume length of each node of the pipes was less than 0.5 m.

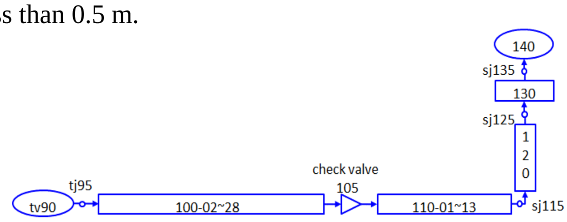

Fig. 3. MARS-KS nodalization of the test loop

The swing check valve was modeled by 'inrvlv' component in built-in model case, while it was modeled by 'srvvlv' component with series of control variables to implement the theory in Section 2.2 for the improved model case.

In the built-in model, if the disk diameter is larger than the pipe diameter, the area of the node just downstream of the valve junction should be large enough to accommodate the movement of the disk.

At an outlet boundary, the atmospheric pressure was imposed at the top of the upper tank.

Water velocity was imposed as an inlet boundary condition. Water was supplied at a constant velocity up to 10.45 seconds, and then the velocity decreased linearly from 10.45 to 11 seconds. According to the experimental data, some backflow was observed just before the check valve was completely closed, so it is very important to reflect this backflow behavior in the boundary conditions. In this study, the inlet velocity behavior presented in the literature [3] was faithfully imposed as a boundary condition.

One problem is that it is unclear whether the mass presented in the literature [3] is a combination of the disk and an arm. If the value is the combined mass of the disk and arm, and if this value is used for input in the calculation of the MARS-KS built-in model, the disk remains in a fully open position. When the value twice the weight was applied, the disk is placed near the steady-state location. This problem should be fed back to code developers.

5. Results and Discussion

Fig. 4 and 5 show a comparison of the disk angle and pressure at P3 location calculated by MARS-KS built-in model with experiment data.

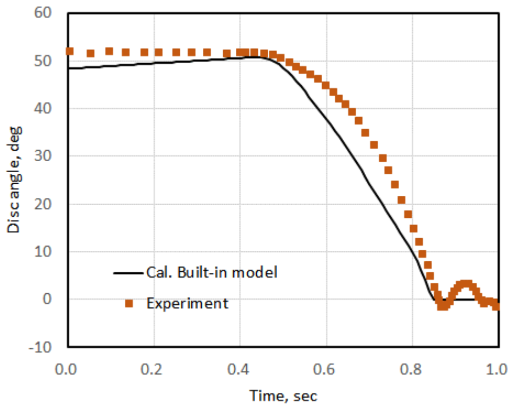

Fig. 4. Comparison of disk angle with test data for the built-in model case

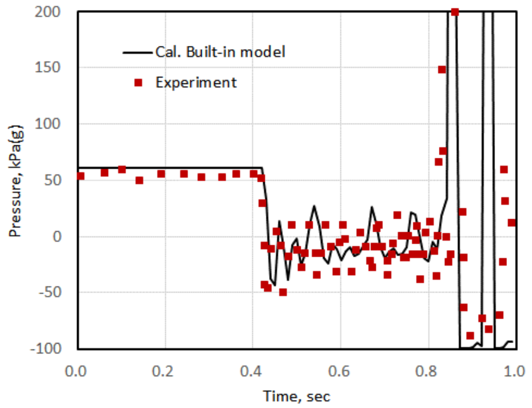

Fig. 5. Comparison of pressure at P3 with test data for the built-in model case

As shown in those figures, overall behavior of check valve closure was reasonably calculated. But

1) The steady-state calculation before 0.4 sec shows that the disk angle is oscillating slowly without converging to a constant value,

2) Although the full closing time of the disk is similar, the predicted closing behavior is different from the experimental data, and,

3) The re-opening of the valve after the closure was not predicted.

Unlike the disk angle behavior, the pressure behavior is surprisingly close to the experimental data, especially predicting a sudden pressure increase due to a water hammer phenomenon that occurs after 0.8 seconds.

Fig. 6 and 7 show comparisons of the disk angle and P3 pressure calculated by the improved model. In contrast to the MARS-KS built-in model, the disk angle during the steady state is stable and close to the experimental data. Although the full closure of the check valve was predicted to be later than the experimental data, the closing behavior up to 0.7 seconds is close to the experimental data.

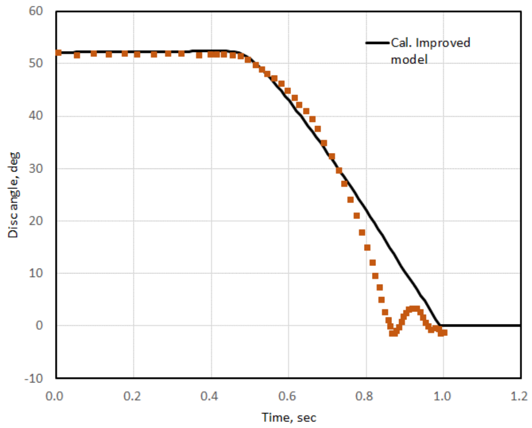

Fig. 6. Comparison of disk angle with test data for the improved model case

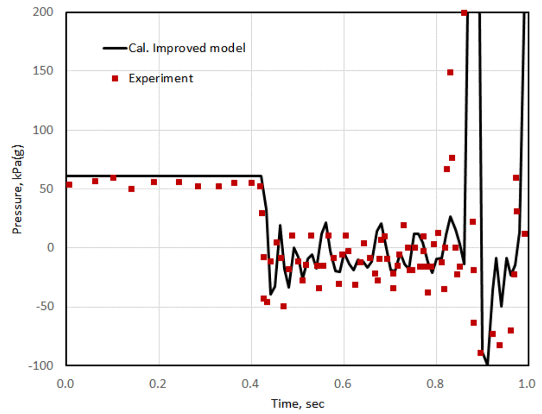

Fig. 7. Comparison of pressure at P3 with test data for the improved model case

The pressure behavior is well agreed with the experimental data as in the built-in model.

The reason why the closing behavior after 0.7 s differs from the experimental data is due to the over-prediction of stationary hydraulic torque and rotational hydraulic torque at small disk angles of 30 degrees or less. In particular, it is necessary to make refined adjustments so that the stationary hydraulic torque becomes a negative value at the time of backflow.

6. Conclusions

To provide an accurate and reliable model simulating the behavior of swing check valves, we examine the built-in model of the MARS-KS code and the improved model presented in the literature [3]. For the latter, the servo valve component was used with series of control variables that implements the angle-dependent variables and the related coefficients. MARS-KS code calculations using those two models were made, respectively, for the experiment of swing check valve closing presented in the literature [3].

It was confirmed that the overall behavior predicted by the improved model was more stable and reliable, although the improved model predicted the full closing time of the valve slightly later than the built-in model. It was found that precise improvement of the stationary and rotating hydraulic torque coefficients is necessary to solve the closing time delay.

ACKNOWLEDGEMENT

The preparation of this paper was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 2106002).

REFERENCES

[1] K.H. Bae et al, Enhanced safety characteristics of SMART100 adopting passive safety systems, Nuclear Engineering and Design Vol. 379, 2021.
[2] KINS, MARS-KS Code Manual, Volume II: Input Requirements, KINS/RR-1822, Vol. 2, Daejeon, Korea, 2018.7.
[3] G. Li, J. C. P. Liou, Swing Check Valve Characterization and Modeling During Transients, Journal of Fluids Engineering, Vol. 125, p1043, 2003.
[4] Information System Lab, REALP5/MOD3 Code Manual, Volume II: Input Requirements, NUREG/CR-5535, 2009.
[5] H.G. Lim et al, Development of a swing check valve model for a low velocity pipe flow prediction, Nuclear Engineering and Design Vol. 236, p 1051–1060, 2006.
[6] Z. Pandula, and G. Halász, Dynamic Model for Simulation of Check Valves in Pipe Systems, Periodica Polytechnica Ser. Mech. Eng., Vol. 46, No. 2 p 91–100, 2002.
[7] B. E. Dallstream et al, Swing Check Valve Design Criteria and CFD Validation, Proceedings of 14th International Conference on Nuclear Engineering, July 17-20, 2006.