Stability Enhancement of Swing Check Valve Model

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1. Introduction

A check valve has been widely used to prevent the reverse flow in many systems including nuclear power plant. When the fluid velocity through the swing check valve is not sufficient enough to meet the minimum velocity, the swing disk increases flow resistance which in turn changes the fluid velocity. Accordingly, the most of the thermal-hydraulic nuclear safety codes have the swing check valve model to fully track the behavior of the flow. [1, 2]

An improved swing check valve model was developed from the previous study to describe the gravity feed in low power and shutdown period [3]. While the developed model has shown good agreement with experiment, this model however, showed oscillatory behavior in disk angle prediction.

In this paper, we develop new angular momentum equation free from oscillation and the valve throat area calculation method for exact prediction of pressure drop in the check valve.

2. Angular Momentum Equation

From the previous study [3], we developed new swing check valve model to improve the mass flow rate under-estimation of MARS code. While the new model is good agreement with experimental data, this model showed oscillatory behavior in the small disk angle range.

Eq. (1) shows the angular momentum equation used in the previous study.

$$I\dot{\omega} = \sum T = \Delta p \cdot A_p \cdot L + \Delta p_F A_d L + K_v \rho_f v_f^2 - \left(\frac{1}{2}M_{arm} + M_{disk}\right) gL \cdot BSin\theta \qquad (1)$$

where, Δp is pressure difference between upstream and downstream of the swing disk, Δp_F is pressure difference to initiate the disk motion (friction), L is hinge arm length, M_{disk} is mass of the swing disk, g is gravity constant, A_P is projected area, D is disk diameter, and, A_D is swing disk area. To improve the oscillatory behavior, new angular momentum equation developed by Botros [4] is applied to the MARS code. The angular momentum equation is expressed as follow:

$$I\frac{d^2\theta}{dt^2} = \left(T_p + T_v\right) - \left(\frac{1}{2}M_{arm} + M_{disk}\right) gL \cdot BSin\theta + \Delta p_F A_d L - C_d D^5 \frac{d\theta}{dt}\left|\frac{d\theta}{dt}\right| \qquad (2)$$

The terms on the right-hand side represents the torques due to hydrodynamic force, gravitational force by disk and disk arm, friction at the seal and the hinge pin, and damping by adjacent fluid. The hydrodynamic force is composed of pressure and impingement component. The pressure force is due to the pressure difference between both sides of the swing disk.

If it is assumed that the pressure distribution in the disk is uniform, the torque by pressure difference is given as:

$$T_p = \frac{\pi D^2}{4}\left(K_b \theta\right)^{-3} \rho v^2 L \qquad (3)$$

In the calculation of hydrodynamic torque by impingement of flow jet, it is assumed that the inlet velocity at the disk is uniform and the outlet velocity is parallel to the disk surface. Considering flow geometry of the swing check valve, the torque by flow jet is expressed as

$$T_v = \int_{A_p} \sin\left(\frac{\pi}{2} - \theta\right) \frac{(L-y)}{\cos\theta} \rho V^2 dA = \rho V^2 \left(LA_p - \int_{A_p} y dA\right) \qquad (4)$$

The detailed induction of the torque by flow impingement is abbreviated due to the lack of space.

The fifth term represents the disk damping effect by adjacent fluid. The previous model showed oscillatory behavior in the disk angle calculation. It was noted that this oscillation was due to the solution scheme since the results of Botros [4] did not show such an oscillation. He used the fourth order Runge-Kutta numerical scheme while we used first order approximation. Since the angular momentum equation coupled with fluid governing equations cannot be differenced with higher order numerical methods without modifying the differencing scheme of fluid governing equations, the damping term is artificially added to dampen the oscillation in this approach.

3. Valve Throat Area Calculation

To calculate the flow field of concerned pipe line, it is necessary to know the flow resistance coefficient of the swing check valve from the disk angle given by Eq. (2). RELAP5 and MARS code have simply calculated the throat area by subtracting the disk projected area from the total valve flow area [1]. Then, the flow resistance coefficient is obtained from the abrupt area change model [1]. This approach over-predict the flow resistance, which gives the swing check valve larger pressure drop, thereby fluid velocities at the flow line significantly decreases (see figure 2). To correct this deficiency, we incorporate the experimental correlation given in Eq. (3) into the abrupt area change model to calculate the valve throat area. The valve is assumed to be an orifice in the code calculation. Combining Eq. (3)

and orifice model of MARS, the following equation can is obtained

$$\varepsilon_T\left(0.62+0.38\varepsilon_T^{\ 3}\right)=\frac{1}{\sqrt{2\left(K_b\theta\right)^{-3}+1}} \qquad (5)$$

Eq. (5) is fourth order algebraic equation which is monotonically increases for a positive value of ε_T. Eq. (5) is solved using Newton-Rapson iteration in the code.

4. Solution Scheme

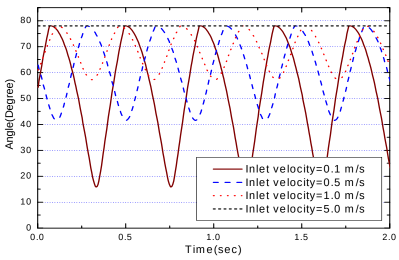
For a given flow geometry including swing check valves, the differenced governing equations of fluid calculate the new time step dependent variables such as pressures, velocities, and etc. The new time velocity passing through the valve is then used to calculate the new time flow geometry, that is, the angle of the valve disk. The difference method for an angular momentum equation of Eq. (2) is identical with that of MARS code [2]. To decouple the angular momentum equation with the fluid governing equations, the explicit numerical method is used for the Eq. (2). By Taylor expansion of angular velocity and neglecting the third order derivative term and further terms, the following approximation for angular velocity is obtained:

$$\theta_{n+1}=\theta_n+\frac{1}{2}\Delta t\left(\left(\frac{\partial\theta}{\partial t}\right)_n+\left(\frac{\partial\theta}{\partial t}\right)_{n+1}\right) \qquad (6)$$

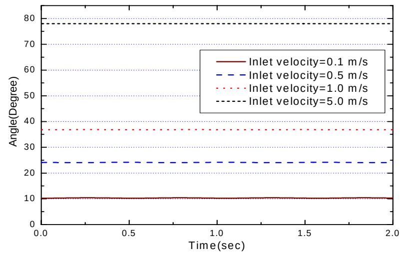
From the new time disk angle given by Eq.(6), the valve throat area can be calculated, the throat area is then used to calculate the flow resistance used in the fluid governing equation.

5. Results and Discussion

To verify the applicability of the present swing check valve model, the analysis for a single swing check valve was performed. Figure 1 shows a comparison with the old model. As shown in Figure 1, the old model severely oscillates at low velocities range, while the new model shows stable disk angle behavior. The present model slightly under-predicts the open angle in the low fluid velocity and slightly over-predicts it in the high fluid velocity (see figure 2). However, the overall prediction of the present model is very consistent with the experimental data.



(a) previous model



(b) Present model

Figure 1. Comparison disk angle behavior

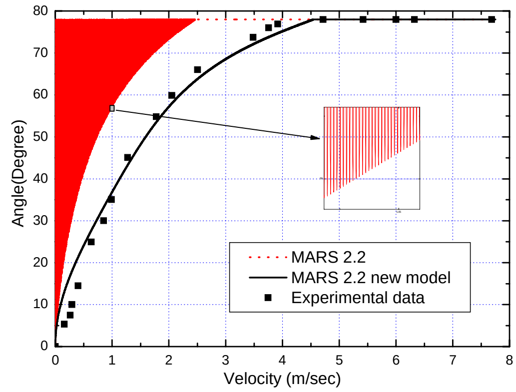


Figure 2. Comparison with experimental Data

6. Conclusion

We improved the check valve model with a newly developed angular momentum equation for the disk of a swing check valve. The developed model was also implemented to the thermal-hydraulic system code, MARS. The present model showed good agreement with test result of single swing check valve in addition to the appropriate damping effect. We expect that the present swing check valve model can be useful to the safety analysis including swing check valve

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