Hydraulic Characteristic of Valves

Valves are integral elements of water distribution systems. Their primary purposes are flow and pressure control, energy dissipation, and system isolation. The opening and closing of valves is one of the primary causes of transient flow in pipe systems and modeling this phenomenon is of great importance.

Valve closure can result in pressures well over the steady state values, while valve opening can cause seriously low pressures, possibly so low that the flowing water vaporizes inside the pipe. For transient analysis, the valve can be considered to be an element of variable resistance where the resistance is related to the closure characteristics of the valve.

The head difference across the valve can be expressed in terms of the valve resistance $C_v$ as:

$$\Delta H = C_v Q^2$$

(5)

From the Orifice Relation:

$$Q = (C_d A) \sqrt{2g \Delta H}$$

(6)

where the product of the orifice area $A$ and the discharge coefficient $C_d$ is frequently called the "effective area" of the valve. Substituting Equation 6 into Equation 5 gives:

$$C_v = \frac{1}{2g C_d^2 A^2}$$

(7)

where $C_v$ is the valve discharge coefficient (typical values range between 0.6 and 0.9). In terms of the valve resistance in the fully opened position, $C_F$, the resistance is given as:

$$C_v = C_F / \left( \frac{A_0}{A_F} \right)^2$$

(8)

The term in parenthesis is the ratio of the open area of the valve, $A_0$, to the fully open area, $A_F$.

The dimensionless valve area opening ratio $A_0/A_F$ ranges from 0.0 (valve fully closed) to 1.0 (valve fully open). The above expressions (Equations 6 and 7) assume that the valve discharge coefficient, $C_d$, remains constant throughout the valve operation.

The fully open resistance term can be computed as expressed in Equation 8 ($A_0 = A_F$) or can be calculated if the head drop, $H_F$, and associated flow rate, $Q$, are known at the fully opened position as:
\[ C_p = \frac{\Delta H_p}{Q_p^2} \]  

Accounting for the effects of changes in the open areas for valves that open or shut during the transient simulation requires a calculation of the open area based on the geometry of the valve.

Five common types of valve are considered. They are called Active Valves and are represented as Motorized Throttle Valves (Throttle Control Valves) in InfoSurge.

These include:

a) Gate Valve,

b) Globe Valve,

c) Needle (Cone) Valve,

d) Butterfly Valve,

e) Ball Valve.

Schematics for valve operations for these valves are shown in Figure 2 below.
The geometric relations for each of these valves were analyzed to obtain the relation for the ratio of the open area, $A_0$, to the area when the valve is fully open, $A_p$, as a function of a translational movement of valve stem expressed as $ZZ_m$ or a turning of the valve stem expressed as $\theta$. These relations are given below.

**Figure 2 – Schematics of Valve Operation**

Case a - Gate Valve (Circular Gate) - Figure 2(a) shows a Circular Gate Valve passing a circular opening. The area for this valve is given by:
\[
\frac{A_0}{A_F} = 1 - \frac{2}{\pi} \left[ \arccos \left( \frac{Z}{Z_m} \right) - \frac{Z}{D} \sqrt{1 - \left( \frac{Z}{Z_m} \right)^2} \right]
\]

where \(Z_m\) is the maximum translational movement from the fully opened to the fully closed position.

Case b - Globe Valve - Figure 2(b) represents a Globe Valve. The flow area is a ring, the height of which is determined by the position of the valve stem. The open area ratio varies linearly and is given simply as:

\[
\frac{A_0}{A_F} = \frac{Z}{Z_m}
\]

Case c - Needle Valve - Figure 2(c) depicts a Needle Valve. The flow is the area between two concentric circles. The area ratio is given by:

\[
\frac{A_0}{A_F} = \frac{2}{\pi} \left( \frac{Z}{Z_m} \right) - \left( \frac{Z}{Z_m} \right)^2
\]

Case d - Butterfly Valve - A Butterfly Valve is shown in Figure 2(d). The area ratio is given by:

\[
\frac{A_0}{A_F} = 1 - \cos \left( \frac{\pi}{2} - \theta \right)
\]

in which \(0 < \theta < \frac{\pi}{2}\).

Case e - Ball Valve - Figure 2(e) depicts a Ball Valve that is described by

\[
\frac{A_0}{A_F} = \left( \frac{1 + \cos \theta}{2} \right) + \frac{\cos \theta}{\pi} \left\{ \arcsin \left( -x \right) + \frac{\sin \left[ 2 \arcsin \left( -x \right) \right]}{2} \right\} - \frac{1}{\pi} \left\{ \frac{\arcsin \left( x \right) + \sin \left[ 2 \arcsin \left( x \right) \right]}{2} \right\}
\]

in which
\[ x = \frac{\sin \theta \sqrt{\left(\frac{E}{e}\right)^2 - 1}}{1 + \cos \theta} \]

in which \( e \) = the diameter of the open cylindrical passage and \( E \) = the diameter of the ball. The angle, \( \theta \), through which the valve stem must be turned to completely close the valve is given by the solution of the following:

\[ \frac{\sin \theta_m}{1 + \cos \theta_m} = \frac{1}{\sqrt{\left(\frac{E}{e}\right)^2 - 1}} \]

Valve Stem Position - The valve stem can be moved in any prescribed manner. The situation usually assumed, is movement at a constant rate caused, for example, by turning a threaded stem at a constant speed. For this situation the valve stem position variable, \( P \), is given by:

\[ P = \bar{P} - \left(\frac{t}{T_o}\right) \Delta P \quad (17) \]

in which \( T_o \) = the valve operation time; \( t \) = the time measured from the initiation of valve operation; \( \bar{P} \) = the initial valve stem position; and \( \Delta P \) = the total change in valve stem position over the time of operation. Here \( \Delta P = ZZ_m \) or \( I_m \) depending on the type of valve stem movement.

Figure 3 below depicts a complete closure operation for these five valves due to a linear movement of the valve stem from the fully opened to fully closed positions. It is possible that the valve stem may be accelerated from the first position to the second position. This type of closure might be expected for fast acting valves such as spring-loaded check valves or solenoid valves. Valves that can be closed with a quarter turn of a lever or a single thrust of a plunger would be expected to close in some sort of accelerated fashion.
Figure 3 – Closure Functions for Standard Valves (Linear Valve Stem Movements)