Control valve design aspects for critical applications in petrochemical plants – part II

This second section of Mr Holger Siemers article on control valve design and sizing continues on from part I, which can be found in the June 2004 issue of Valve World. This section presents information on design, size and use of severe service control valves, the kind of troubles that can be predicted with control valve sizing as well as suggestions for troubleshooting control valve failures. The final section, part III, will be ready and waiting in the upcoming October issue.

4) Predictable troubles with control valve sizing in case of sub-critical flow conditions

It is well-known that sensitive valve sizing areas exist with supercritical gases and slightly sub-cooled or non-sub-cooled liquids (flashing). Vapors and gases are calculated with the isentropic exponent \( k \) as one of the property values. Some hydrocarbons, e.g. ethylene, are near or above the “critical points \( t_{\text{crit.}} \) and \( p_{\text{crit.}} \)” during the process.

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Critical flow

Predictable control instability, if application data are near the critical point because of sudden change of density and isentropic exponent.

Not critical flow

Incorrect result:
\[
C_v \text{ calc} = 81 \\
xT = 0.2
\]
at operating point
wrong \( k = 1.2 \)
Correct result:
\[
C_v \text{ calc} = 59 \\
x = 5.6 !
\]
Range of \( x \) from \( p_1 = 60 \) to \( 70 \) bar and \( t_1 \) from \( 12 \) to \( 16 \) °C

Fig. 16: Sensitive sizing areas in case of supercritical flow “isentropic exponent above the critical point” > 2
The sizing standard IEC 60534-2-1 includes an information table with typical isentropic exponents used for steam and gas sizing. The total range 1 < k < 2 is well-known for all compressible fluids. However, it is less-well-known that values 2 < k < 20 exist with supercritical fluids near and above the property critical point.

We would like to introduce this matter with the help of latest development in precise property calculation, published at the Ruhr University of Bochum for more than 60 industrial gases and integrated into the CONVAL® software.

The third case study shows tremendous sizing differences in flow calculation for an ethylene application at the critical point of properties by using the real isentropic exponent >> 2. This can have a negative influence on plant safety valves and other devices. In the past, devices for supercritical flows were oversized because the wrong isentropic exponents and “choked flow limits” were used. We are interested to start an open discussion on how to define and handle this phenomenon and on how to validate it with measurements.

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**Table 3: Available substances calculated with thermodynamic equations**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Substance</th>
<th>Substance</th>
<th>Substance</th>
<th>Substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Butene</td>
<td>Diethylether</td>
<td>Isohexan</td>
<td>Pentane</td>
<td>R125</td>
</tr>
<tr>
<td>Air</td>
<td>Dichlorodifluoromethane</td>
<td>Isopropylbenzene</td>
<td>Phenol</td>
<td>R134a</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Difluoroethane</td>
<td>Krypton</td>
<td>Propane</td>
<td>R141b</td>
</tr>
<tr>
<td>Argon</td>
<td>Ethane</td>
<td>Methane</td>
<td>Propylene</td>
<td>R142b</td>
</tr>
<tr>
<td>Benzene</td>
<td>Ethylbenzene</td>
<td>Methanol</td>
<td>Propylene</td>
<td>R143a</td>
</tr>
<tr>
<td>Butane</td>
<td>Ethylene</td>
<td>Natural gas</td>
<td>SF6</td>
<td>R152a</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Fluorine</td>
<td>Neon</td>
<td>Toluene</td>
<td>R121</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Helium</td>
<td>Neopentane</td>
<td>Water</td>
<td>R22</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Hexane</td>
<td>Nitrogen</td>
<td>Xenon</td>
<td>R23</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>Hydrogen</td>
<td>Nitrous oxide</td>
<td>R11</td>
<td>R32</td>
</tr>
<tr>
<td>Cyclopentane</td>
<td>Hydrogensulphide</td>
<td>Nonane</td>
<td>R12</td>
<td>R41</td>
</tr>
<tr>
<td>Cyclopropane</td>
<td>Hydrogen</td>
<td>Octane</td>
<td>R123</td>
<td></td>
</tr>
<tr>
<td>Decane</td>
<td>Isobutane</td>
<td>Oxygen</td>
<td>R124</td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 17:** Example of warning indicators in a hot water application to indicate the onset of cavitation and flashing at smaller loads. If not controlled below Op2 no risk, if often control smaller loads < Op2, valve DN too small.

**Fig. 18:** Dynamic plant system: – pressure versus flow.

**Fig. 19:** Typical damage due to cavitation if pressure differential > 20 bar. Feedwater control valve mismatched for start-up 70 to 1 bar.

**Fig. 20:** Damage due to flashing if p2 << pv and v2 >> 60 m/s.

**Fig. 21:** Damage due to a rotary plug body due to cavitation v2 >> 5 m/s.

**Fig. 22:** Damage due to steam pressure letdown Ma >> 1.
Predictable troubles with control valve sizing in case of flashing as well as installation cost saving which results in poor planning parameters

Figure 17 shows an example of warning indicators in a hot water application to indicate the onset of cavitation and flashing at smaller loads. If not controlled below Op2 no risk, if often control smaller loads <Op2, valve DN too small.

CONVAL calculates real thermodynamic flashing conditions with about sixty hydrocarbons [see Table 3] and recommends the minimum valve DN to avoid critical outlet velocities. The calculations resemble steam table mathematics. This is based on a reliable source,

Installation cost saving which results to poor planning parameters

Detecting planning mistakes: qmax > 0.9 q100, Δp at qmax too small. See Figure 18.

5) Control valve failure and troubleshooting.

Ranging from seat guided V-port to CFD optimized trims and their applications. There are different solutions to avoid critical sound and mechanical valve failure (see Figures 19 through 22). This section introduces anti-cavitation valve trim designs [2] and noise attenua-

Table 4: Different trim designs and their advantages and disadvantages in severe service applications.
tion devices and discuss their advantages and disadvantages as well as their application limits. Note that too high velocities at the valve moving parts and at valve outlet are mainly responsible for valve failure especially where corrosive fluids are handled.

SAMSON AG offers under strong limitations of valve outlet velocities and other parameters the high performance V-port trim for general service; flow dividers I and III and downstream low noise devices for gas and steam pressure letdown. See Figure 23.

If the V-port trim sound pressure level (SPL) is not acceptable for liquid applications or cavitation and corrosion must be avoided in general, the unique AC Trim System is recommended (see Figures 24 and 25) with top and seat guided plug, vibration-free and dirt-insensitive. The max. pressure differential 25 to 40 bar depends on the fluid properties. For case histories of troubleshooting with the AC Trim system, please see Figures 26 and 27. Further, Table 4 gives an overview of the advantages and disadvantages of different trim designs.

AC Trim III system multistage design

The AC Trim III System is ideal for liquid application to avoid cavitation, wear and noise (see Figure 28). Features include top and seat guided plug, vibration-free and dirt-insensitive, with/without pressure balance, pressure differential 25 up to 120 bar; AC Trim V System-5 stages-120 bar < Δp <200 bar. Three and five stages in the cv range from Cv =1 (3 stages) to Cv=116 from DN 1 to DN 6 inch in globe and angle type valves are used in case of severe cavitation problems e.g. high Δp together with a larger control range qmin to qmax. Typical applications are feed-water start-up valves, refinery valves, snow gun valves, injection valves, boiler applications, high pressure letdown service, etc.

6) The hidden valve enemy: Critical outlet velocities need to take priority

Beating “quick and dirty” sizing philosophies, if selecting too small valve DN taking only the calculated Cv value into account. High flow capacity valves (Cv/DN²) need to be selected with care when critical operation conditions are involved. Rule of thumb to avoid mix phase flow: in case of pv equal or near to p1 avoid 20xDN any pipe restriction at valve upstream, no elbows, no manual valves, no pipe reducers.

Sensitive sizing areas special valve DN selection by giving priority to the outlet velocity condition of cavitation and flashing in liquid application and gas and steam pressure letdown, taking important piping parameters into account.

In case of flashing conditions, the average outlet velocity has to be calculated for the mixture of liquid and wet steam or vapour. Severe pipe vibration and valve damage can be avoided if the valve outlet diameter restricts the outlet velocity to less than 60 m/s (average of 0.7 Ma of mixture sonic speed). SAMSON has developed equations of state for flashing outlet velocities used in CONVAL for all fluids in Table 3.

To be continued.

Table 5: Recommendations to reduce cavitation erosion [2]. Using table 5 for non-corrosive liquids with cavitation: Xf>Xz

- Outlet velocity should not exceed 2m/s to max 5m/s depends on valve design
- Low vibration valve plug design like seat, cage or top and bottom guided plugs.
- Low cavitation erosion: Δp < Kc • (p1-pv) or Δp < Apcrit,cav , if Δp > Kc • (p1-pv) !
- Cavitation erosion: Δp > Kc • (p1-pv) and Δp > 25 bar -> multistage globe valves (like AC Trim III System)

<table>
<thead>
<tr>
<th>Valve design</th>
<th>Kc</th>
<th>Apcri,cav [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-stage globe valves with stellited or hardened valve plug and seat</td>
<td>0.7</td>
<td>25</td>
</tr>
<tr>
<td>Single-stage globe valves with standard materials</td>
<td>0.7</td>
<td>15</td>
</tr>
<tr>
<td>Rotary plug valves (with eccentric spherical disk)</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>Butterfly and ball valves</td>
<td>0.2-0.3</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 29: Flashing Photo SAMSON AG test rig [2]

Fig. 30: The thermodynamic flashing process. T = temperature; s = entropy; K = critical point.

Fig. 31: Plant shutdown due to “quick and dirty” sizing with 8 inch rotary plug valve and too small DN. Non-subcooled naphtha p1 = pv. The application requires a 12 inch valve to avoid the risk of sonic speed “choked flow” at the valve outlet.