Using ball valves in high-temperature applications

Ball valves (Fig. 1) are often an economical solution for controlling flows in refinery high-temperature applications, but their application can be complex, particularly in high-temperature uses.

For the purposes of this article, “high-temperature” is considered as anything higher than 400°F (204°C). Although API RP 615 defines high-temperature service for metal-seated valves as temperatures greater than 750°F (400°C), 400°F (204°C) is a natural transition temperature where most elastomers and polymers break down. Also, some softer metals, such as aluminum alloys, begin to weaken as temperatures increase. Most refinery applications are less than 1,500°F (816°C).

Reviewing industrial valve reference documents will not assist end users in understanding all of the critical aspects associated with high-temperature valve constructions because the information found in these sources is usually generic, such as recommending that plastic components be replaced with metal or graphite. General service valves cannot be repurposed for high-temperature service, as these applications require a solution where all parts of the valve/actuator assembly are addressed.

This article examines the design and testing of ball valves for use in high-temperature refinery applications. End users can work with suppliers to apply this information when specifying ball valves.

Applications. Petroleum refining requires many high-temperature processes to separate crude oil into marketable oils and distillates. High-temperature valves are nothing new to the industry, although applications continue to migrate toward higher temperatures. Ball valves have not always been the valve of choice. However, trunnion and floating ball valves are being used more frequently due to flow efficiencies and compact form factors. Some of the most common applications and maximum temperatures include:

- Hydrocracker feed: 650°F (343°C)
- Gas plant debutanizer bottom product: 650°F (343°C)
- Hydrotreater: 750°F (399°C)
- Catalyst in hydrocracking: 950°F (510°C)
- Coker crude oil bottoms, furnace feed, coke slurry, drum switching, blowdown and overhead vapor: 970°F (521°C)
- CCR and FCCU catalyst handling, flue gas and fractionator bottoms: up to 1,400°F (760°C).

A steam power plant in a refinery may also require dozens of condensate drain valves and vents with temperatures exceeding 1,000°F (538°C). ASME TDP-1 requires drain valves to have a minimum flow area equivalent to 85% of the adjacent pipe, essentially favoring full-port ball valves for these applications.

Drivetrain performance. In high-temperature applications, poorly designed valves can fail quickly in multiple ways. A common mode of failure is the binding of drivetrain components. Depending on the severity of binding, one can expect accelerated wear on metal parts or a complete stall out of ball rotation. Actuator torque can exceed the capability of the drivetrain, resulting in sheared keys, a twisted shaft and/or a deformed ball. A coating failure of the ball to seat (Fig. 2) may also occur.

Drivetrain friction goes up with increases in temperature. During normal operation, torque may increase up to two times compared to what is experienced at ambient temperature, thereby making actuator sizing critical. Factors influencing this increase in torque include the shifting of parts due to thermal expansion, thermal growth of complex geometries and the dissipation of assembly lubricants, such as molybdenum disulfide. Metal bearings and graphite packing rings have higher friction than polymer equivalents, and the softening of load-bearing parts results in higher friction and the potential for galling or wear.

Trim troubles. Trim components within the valve assembly must not only be compatible with the fluid; they must also be
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capable of withstanding high stresses. Valve stems absorb the brunt of the torque required to actuate the valve, so they should be made from a corrosion-resistant material that maintains high yield strength and torsional stiffness at elevated temperatures, such as Inconel 718, 17-4 stainless steel or Nitronic 50.

Since the ball and seats are in the flow stream, the only option is a metal-to-metal seal. Obtaining tight shutoff with metal seats provides a greater challenge than with soft seals. To maintain a leak-free joint between the ball and seats, the following parameters must be controlled: fit of parts, surface finishes and a contact stress that provides the desired shutoff while not damaging the coating. If the design cannot satisfy these requirements, then excessive seat leakage will occur.

Metal bearings, particularly stainless steels, are usually coated to reduce friction and minimize wear. To aid in reducing the rate of wear, the contact stress between the stem and bearings should be reduced. Some materials, such as duplex and precipitation-hardened stainless steels, can become brittle at elevated temperatures. In extreme applications, ceramic trim and linings may be used due to their excellent erosion/corrosion resistance and high-temperature strength.

**Internal coatings.** Hardening the outer surfaces of various trim components can extend usable life. Some of the more common hardening methods are:

- Chrome carbide and tungsten carbide, applied by high-velocity oxygen fuel thermal spray, can be used up to 1,500°F (816°C). Tungsten carbide is the preferred coating below 900°F (482°C), due to its superior abrasion and erosion resistance at lower temperatures. Hardness value should be a minimum of 65 Hardness Rockwell C (HRC).
- Spray coatings can be fused via a secondary oven or manual torch operation to ensure a proper metallurgical bond with the substrate, thus eliminating coating spalling. These coatings are especially hard, at about 65 HRC, and maintain their hardness across a wide range of temperatures.
- Alloy 6 weld overlays can be used up to 1,800°F (982°C), but are normally limited to 1,000°F (538°C) due to softening. This material has many desirable aspects, such as good resistance to corrosion, galling, oxidation (regardless of temperature) and thermal shock. The typical hardness for Alloy 6 ranges from 36 HRC–40 HRC.
- Hard chrome plating is recommended for temperatures up to 800°F (427°C). It can be used at higher temperatures, but its hardness diminishes as temperatures exceed 800°F (427°C). Results from laboratory tests indicate that chrome plating will lose half its hardness as temperatures approach 1,200°F (649°C). The expected hardness for chrome plating is approximately 65 HRC.
- Nitriding is a thermochemical case-hardening process. Unlike other hardening processes, material is not deposited onto the base metal. With nitriding, the outer surface of the part is hardened, and the hardness decreases as one goes further into the part. Nitrided parts can be used up to 1,500°F (816°C).

The overall quality associated with a coating is influenced by the condition of the base material and its application. Therefore, a coating should be evaluated through testing to verify its capabilities. One way to accomplish this is through wear tests at temperature (Fig. 3).

**Centerlines and clearances.** A material's coefficient of thermal expansion is the average ratio of the change in length per degree in temperature to the length at a given minimum temperature, expressed as in./in./°F or mm/mm/°C. For example, when a 316 stainless steel sphere with a diameter of 10 in. and an average coefficient of thermal expansion of 9.7 × 10⁻⁶ in./in./°F is heated from 70°F (21°C) to 500°F (260°C), it will ex-

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**TABLE 1. Expansion coefficients**

<table>
<thead>
<tr>
<th>Material</th>
<th>Average expansion (in./in./°F) 70°F to 500°F</th>
<th>Average expansion (in./in./°F) 70°F to 1,000°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A105</td>
<td>7.3 × 10⁻⁶</td>
<td>8.1 × 10⁻⁶</td>
</tr>
<tr>
<td>F22</td>
<td>7 × 10⁻⁶</td>
<td>8 × 10⁻⁶</td>
</tr>
<tr>
<td>F316</td>
<td>9.7 × 10⁻⁶</td>
<td>10.3 × 10⁻⁶</td>
</tr>
<tr>
<td>F6a</td>
<td>6 × 10⁻⁶</td>
<td>6.6 × 10⁻⁶</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>7.3 × 10⁻⁶</td>
<td>7.8 × 10⁻⁶</td>
</tr>
</tbody>
</table>

**FIG. 2.** Trunnion ball showing coating failure near the bore and trunnion bearing surface.

**FIG. 3.** Ring and block wear coating samples tested at elevated temperature. The coating held up well to this test. It has a relatively smooth, uniform wear band that shows minimal signs of galling.
expand to a diameter of 10.042 in. Since this coefficient changes with temperature, that same sphere will expand to 10.096 in. at 1,000°F (538°C). Table 1 shows some coefficients of thermal expansion for various materials and temperatures.

Since different materials have different expansion rates, material selection impacts operation. An unfortunately common and worst-case valve example is 300 series stainless steel trim in a carbon steel (A105) body. Although this combination may provide an economical solution at ambient temperature, the much higher rate of expansion for stainless steel can result in the trim expanding into the body at high temperatures, leading to drivetrain binding. A better alternative is to use F6a or Inconel 625 trim in a carbon steel body.

The concern with different expansion coefficients is exacerbated by the fact that not all valve components are at the same temperature because thermal gradients within a valve are common. In high-temperature applications, this often results in the trim expanding more than the body, which leads to drivetrain binding.

Throttling valves usually open slower, allowing the parts within the valve assembly more time to equalize. On/off valves have a higher burden because a sudden rush of hot fluid occurs when they go from closed to full open, but smaller bypass valves can be used to mitigate this issue.

Stem seal considerations. The inability to use most polymers and elastomers above 400°F (204°C) presents a challenge in seal design. Graphite has become the status quo for most high-temperature seals despite its limitations. Graphite stem packing can experience oxidation, consolidation and/or extrusion—leading to premature seal leakage.

To minimize oxidation, the temperature of the packing set should be limited to 850°F (454°C) in oxidizing environments, and to 1,200°F (649°C) in non-oxidizing services, such as steam. Keeping the packing rings below this limit can be accomplished by using bonnet and stem extensions and/or lantern rings, both of which serve as insulators. As a rule, any refining applications over 800°F (426°C) water at 650 psi (45 bar) for 35 d, looking for wear, are common. In high-temperature applications, this often results in the trim expanding more than the body, which leads to drivetrain binding.

Consolidation is the filling of internal voids within the packing ring and the packing box chamber that occur during initial assembly of the packing rings. Additional consolidation can occur over time as the graphite rings continue to densify under load and temperature.

Consolidation can be minimized by using high-density graphite rings, designing to an appropriate packing stress and using an assembly procedure focused on compressing each graphite ring to its target stress, as opposed to compressing the stack of rings simultaneously.

Extrusion occurs when portions of the graphite rings are pushed out of the packing box because of loads produced by the packing studs and/or pressure from the process fluid. It is necessary to minimize clearance between the stem and the body/bonnet to limit the amount of extrusion—a difficult task, considering that these materials thermally expand at different rates. If the clearance is too large, the rings will extrude. If the clearance is too small, the stem rubs or binds on the body/bonnet. Carbon rings or metal washers can be implemented above and below the packing set to minimize extrusion.

Packing problems. “Live loaded” packing uses springs to obtain a constant stress in the packing studs and packing rings to compensate for small amounts of oxidation, consolidation and extrusion. Springs can be placed over the packing studs and under the nuts, although larger springs that surround the stem (Fig. 4) provide a more consistent load over time. These live-loaded packing sets benefit from occasional adjustment, with best performance occurring with this regular maintenance.

Determining an appropriate torque for the packing studs is critical to the valve’s performance. Ball valves in high-temperature applications experience flow-induced vibration and thermal cycles as the ball rotates from a closed position to an open position. If the bolt torque is too low while the valve is in service, then the packing nuts may loosen and cause a packing leak. Excessive bolt torque leads to excessive valve torque, which may result in the valve failing to operate, or cause a “stick/slip” behavior in a control valve, leading to poor control of flow.

API 622 uses two tests to qualify valve packing up to 1,000°F (538°C). High-temperature corrosion testing uses a fixture to apply compressive stress to the packing set while soaked in 300°F (149°C) water at 650 psi (45 bar) for 35 d, looking for wear. A packing material test measures weight loss due to oxidation while ratcheting soak temperatures up to 1,000°F.

Packing sets passing these tests can be used in a ball valve tested to API 641 for fugitive emissions, although this test is limited to 500°F (260°C) due to the use of methane. An alternate international fugitive emissions test, ISO 15848, can go up to a standard temperature class of 752°F (400°C) with helium, although higher temperatures could be tested upon agreement between the manufacturer and purchaser. Other minerals, such as mica or vermiculite, can be used as packing up to 1,800°F (982°C) and, unlike graphite, will not pit stainless steel valve stems. Coordination with a packing vendor is necessary for these special applications.

Body gasket considerations. Static seals have a little more freedom in design. Gaskets can be made from graphite or metal, and graphite gaskets can be flat sheet or spiral wound. Flat-sheet gaskets are compressed and enclosed between two metal surfaces. A spiral-wound gasket is semi-metallic, comprising a spirally wound V-shaped metal strip and a graphite filler material (Fig. 5).

Spiral-wound gaskets used between pipe flanges typically come with an inner and outer ring. These rings provide centering, compression control and augmented gasket stiffness. Spiral-wound gaskets used inside a valve assembly do not have inner and outer rings, so these gaskets are considered “special” because the metal windings must produce the stiffness once provided by these rings.

Designing in the proper amount of gasket stiffness without losing sight of its ability to seal becomes more difficult as the pressure class and size of gasket increase. Spiral-wound gaskets are limited to CL2500 ratings and may be assembled only once. After that, the gasket has been deformed too much for reuse. To obtain the proper compression on spiral-wound gaskets, larger-diameter bolts are required when compared to a bolted joint that utilizes an O-ring or metal bore rings. For graphitic-type gaskets, leakage to atmosphere may occur if bolt loads relax.

Metal bore rings (Fig. 6) are self-energized and pressure-energized seals that offer an alternative to graphite-based gaskets. The seal ring is clamped between two mating parts, and as the
body halves are drawn together, contact eventually occurs with the ring.

A controlled compressive load is applied to the ring, such that permanent deformation is avoided. This type of seal provides several functional benefits. It is reusable, prevents leakage during thermal transients regardless of temperature, and has been successfully used in valves up to CL4500 pressure ratings.

**Lab testing.** Production tests of shell integrity and seat leakage, to both ASME B16.34 and API 598 standards, are performed at ambient temperature and provide insufficient insight into the operation of a valve at elevated temperatures. This type of verification requires testing by the manufacturer in a laboratory.

Testing can involve heating the valve from the outside, either in a kiln or wrapped in heat tape (FIG. 7), and testing to check for leakage, torque and part wear. Thermocouples are used at multiple locations on the valve assembly to ensure that the temperature equalizes throughout.

Tests normally use hot air, helium or methane as the process fluid. Steam testing, where the fluid heats the valve from the inside, may also be used to gauge the operation of the valve under thermal shock, as would be experienced in operation. Although this may better represent the temperature gradients in operation, the steam can act as a lubricating fluid, which may reduce measured torques.

Industry tests can also be used to gauge high-temperature operation. API 641, ISO 15848-1 and Shell 77/300 all measure fugitive emissions at elevated temperature, with the latter also looking at seat leakage across the temperature range. API 607 and API 6FA fire testing evaluates seat and external leakage, operability and cavity pressure after the assembly is exposed to flame for 30 min.

Regardless of the test, lab environments are different than actual applications because the test fluids are less corrosive and free of the particulates that may induce wear. Thermal gradients are nonexistent or less than what will be experienced in service. As a result, field trials are recommended to prove the solution prior to application on a large scale.

**FIG. 4.** A live loaded graphite packing arrangement for ball valves uses springs on the valve stem to provide a constant load.

**FIG. 5.** Cross-section of a spiral-wound gasket showing alternating bands of stainless steel windings and graphite filler.

**FIG. 6.** Metal bore seal ring clamped between two valve body halves.

**FIG. 7.** A valve wrapped in heat tape and insulation and instrumented with multiple thermocouples.

**Other considerations.** Pressure-temperature ratings are given for common materials in ASME B16.34, with the temperature of the shell assumed to be the temperature of the fluid. Although a valve nametag may list a maximum temperature, this may relate
only to the shell integrity and does not guarantee proper operation at that temperature. It is important that the end user communicate to the supplier the range of temperatures at which the valve must operate, and not just specify a pressure class and material.

The need for external coatings is questionable in high-temperature applications, with the most benefit being realized by steel valves during shipping and plant downtime. Steel valves will rust at ambient temperatures, but not at high temperatures. During shipping, installation and startup, these valves are at low temperature and may be exposed to moisture, causing rust. Wet spray and powder coats are limited to approximately 300°F (149°C). Inorganic zinc coatings, with or without silicone top coats, provide galvanic corrosion protection to steels at temperatures up to 1,000°F (538°C) and are a popular choice. Considering the complex relationship of base material, base coats and top coats, advice should come from the coating manufacturer.

Bracket designs intended for high temperature must have a higher factor of safety to account for larger actuators, while also accounting for lower bracket, bolting and coupling strength at elevated temperatures. The distance from the valve to the actuator or manual operator must be adequate to protect elastomers and personnel. These applications often use insulation around the pipe and valve body to minimize heat loss.

Whereas a standard actuator with nitrile seals and polymer bearings may be rated only to 200°F (93°C), high-temperature constructions with fluorocarbon elastomers and metal bearings may extend the range up to 350°F (177°C). Even if the actuator can handle higher temperatures, accessories such as airsets, boosters, positioners and solenoids may need to be remotely mounted in a cooler area.

**Recommendations.** Many refinery processes call upon engineered ball valves to operate at high temperatures where elastomers and polymers cannot be used. These valves can operate successfully when a holistic approach is taken during the design, including the selection of materials, actuation and accessories. Even with attention to these details, the severity of these applications requires a program to test and verify performance.

End users specifying and purchasing these types of valves can use the information presented in this article to improve their ball valve and vendor selection process.