Mixing: Innovative Designs and Agitator Seals

Reliability and Maintenance

Developments in Petroleum Refining

Protecting Industrial Control Systems

Monitoring Flame Hazards

Combustible Dust Standards

Facts at Your Fingertips: Insulating Heat-Transfer Piping

Focus on Pipes, Tubes and Fittings

page 42
Cover Story

42 Part 1 Mixers: Four Innovations Worth a Closer Look
Many factors can impact the success of mixing in chemical process operations. The design breakthroughs profiled here address some of the most commonly encountered issues.

50 Part 2 Reliable Operation and Sealing of Agitators
Mechanical seals, as required by most vessel agitators, are systems sufficiently complex to warrant a good understanding by engineers and good training for operators.

In the News

7 Chementator
Making complex silicone parts by 3-D printing; Syngas-to-lipids process demonstrated; A joint effort to enable the production of sulfur-enhanced urea at large scale; Microbes make a meal of PET; Extremophilic algae selectively recover precious metals from solution; and more.

14 Business News
TCV begins construction of new liquid polybutadiene plant in France; Vertellus completes expansion for DEET insect repellent; Linde to build air-separation unit in Malaysia; Startup of new purified terephthalic acid line in China; Praxair signs contracts with glassmaker; and more.

16 Newsfront New Developments Take Shape for U.S. Petroleum Refiners
Process safety strategies, water use and alkylation were among the topics figuring prominently at the 2016 AFPM meeting.

22 Newsfront Protecting Your Industrial Control System
A holistic and proactive approach to cybersecurity can help protect your industrial control system from hackers.

Technical and Practical

38 Facts at your Fingertips Insulating Heat-Transfer Fluid Piping
This one-page reference provides information about insulation used for heat-transfer fluid systems.

40 Technology Profile Styrene-Butadiene Rubber via an Emulsion Process
This column describes a process for making styrene-butadiene rubber using an emulsion-based approach.

58 Feature Report Part 1 Equipment Reliability Trends of Top Performers in the CPI
Focusing on a “reliability culture,” mechanical availability and optimum costs leads to top performance.

65 Feature Report Part 2 Integrated Risk-Management Matrices
An overview of the tools available to reliability professionals for making their organization the best-in-class.
To ensure safe and reliable agitator operation, the sealing of the rotating shaft is of fundamental importance. Depending on the operating conditions — such as pressure, temperature and speed — various sealing principles may be used. A comparison of their characteristics with the requirements for mixing shows that mechanical seal technology offers many advantages over other sealing methods. In particular, when hazardous substances are being mixed or an explosive atmosphere is present, the use of a mechanical sealing system is almost mandatory, especially if the mixing vessel operates at elevated pressure and temperature.

**Agitator seal systems compared**

A reliable mechanical design for an agitator (Figure 1) must take into account the hydraulic loads on the impellers, which in turn create the torques and bending moments that exert mechanical loads on agitator components such as the shaft, bearing and gearbox. Secondary loads, such as oscillations, vibrations and noise emissions also play important roles.

Shaft seals can be divided into two main groups: radial and axial seals. The main difference between these two groups is the direction in which the contact forces act.

Typical types of radial shaft seals include radial sealing rings, lip seals and stuffing boxes. Here, the sealing effect is provided by radial forces, and the length of the cylindrical sealing gap is in the axial direction. Although radial seals are relatively insensitive to axial displacement, radial shaft deflections lead to higher sealing forces on one side, which may cause leakage and accelerate wear.

In contrast, the sealing forces in axial shaft seals act in the axial direction. This results in a horizontal sealing surface with a concentric circular cross-section. Owing to their design, axial shaft seals are relatively insensitive to radial shaft deflections and are thus very suitable for agitator applications. Axial displacements have to be compensated with elastic elements. Mechanical seals belong to the group of axial shaft seals. Below, some examples of each type of seal are discussed in more detail (see also Figure 2).

**Stuffing boxes.** Historically, stuffing-box packings are the oldest type of sealing element. The term “stuffing box” originates from early steam ship construction. The passage for the shaft through the hull was sealed with oil-soaked rags that were stuffed into the gap between the shaft tube and the housing. The first mixing vessels were often equipped with a stuffing box.

**Lip seals.** In mixing applications, the working principle of lip seals can be in either the radial
or the axial direction. Cup collars, which provide axial sealing, can be shifted to different positions along the shaft. A cup collar whose lip runs along the surface of the mounting flange can protect surrounding equipment from steam or other vapors inside the mixing vessel, though it works only for vessels operating at atmospheric pressure. Radially acting lips — usually made from a modified polytetrafluoroethylene (PTFE) material — are also used to seal mixing vessels. These shaft lip seals, however, must be equipped with relatively complicated bearings to limit shaft deflections within the seal housing to about 0.01 mm. This is the only way to operate the lips reliably at pressures of up to 6 bars.

**Hermetic seals.** To hermetically seal a mixing vessel using only static seals, the mechanical energy required at the impellers must be transmitted through the wall of the closed vessel. The input torque of a magnetic drive is transmitted to the shaft through a canister using permanent magnets.

**Mechanical seals.** Mechanical seals with dynamic sealing elements are regarded as technically tight when pressurization of the seal liquid is able to maintain a positive pressure gradient between the seal liquid chamber of the mechanical seal and the product in the vessel. Most mechanical seals used with agitators have two pairs of sealing rings: two rotating and two stationary rings (Figure 3). These pairs of rings form an enclosed space — the seal chamber — that can be filled with seal liquid. The contents of the vessel can be reliably sealed against the surroundings by applying pressure to the seal liquid.

If the seal-chamber pressure is controlled so that it is always higher than that inside the vessel, the product inside the vessel cannot get past the mechanical seal. However, the unavoidable leakage of seal liquid past the inboard sealing rings will enter the vessel, while leakage past the outboard pair of sealing rings will enter the surroundings.

The design principles of mechanical seals can be divided into single- and double-acting seals. Another differentiating feature is the type of seal-ring lubrication: dry-running, gas-lubricated or liquid-lubricated.

**Single-acting mechanical seals.** The key design feature of single-acting mechanical seals is that they have only two seal rings. This means they have only one interface and no seal-liquid chamber. A key characteristic of single-acting mechanical seals is that they can leak into the surroundings of the vessel. The leakage rates are generally not high: about 10–100 mL/hr of gas for dry-running seals and 10–50 mL/d of liquid for side-entry mechanical seals. This means that the vessel is not technically tight, in contrast to double-acting mechanical seals. Therefore, this seal design cannot be used when hazardous materials are to be mixed.

Although dry-running mechanical seals do not need seal-liquid supply systems and their corresponding monitoring devices, the seal rings are subject to relatively high wear. The service life is therefore much lower than that for liquid-lubricated mechanical seals. Nevertheless, dry-running mechanical seals...
can achieve service lives of a year or more under appropriate operating conditions. Liquid-lubricated single-acting mechanical seals can achieve much longer service lives, where the nature of the product allows them to be used. Many applications involve suspended solid particles that—depending on their hardness and particle-size distribution—can greatly influence the service life of the seal rings. These seals are generally equipped with two seal rings made from abrasion-resistant silicon carbide (SiC). However, the use of two hard materials is not ideal with respect to sliding friction. In this case, it is usually better to use a softer material for one of the faces, accepting higher wear in return for lower friction.

**Double-acting mechanical seals.** Double-acting liquid-lubricated mechanical seals are the most common type for mixing applications, where they can be used under nearly all operating conditions. They are also available in gas-lubricated variants, in which a continuous supply of gas into the seal chamber maintains a seal gap of a few micrometers, thus preventing wear of the seal rings. The characteristic feature of a double-acting mechanical seal is its seal-fluid chamber that can be filled with seal liquid or gas, thus separating the interior of the vessel from its surroundings.

Figure 2 shows how the various types of seals discussed above score against process parameters such as temperature and pressure, plus broader criteria like cost and service life. It is obvious that mechanical seals offer many advantages over the other types. Particularly if hazardous or explosive materials are being mixed, a mechanical seal is practically mandatory. A hermetic seal with a canister in combination with a mechanical seal is used for applications requiring the highest safety, such as hydrogenation or phosgenation reactions.

### Basics of mechanical seals

A mechanical seal system, as shown in Figure 3, has several components. Alongside the mechanical seal cartridge itself are the hydraulic components (such as a pressure compensator), and the rest of the installation, comprising the pipework, instrumentation and mountings. Some applications also include a seal-liquid refilling system. As a consequence, in most mixing systems, reliable sealing depends on the complete mechanical seal system. Careful selection of suitable hydraulics and installation components is just as important as the design of the mechanical seal itself.

The function of a mechanical seal is essentially governed by the mechanisms taking place in the gap between the rotating and the stationary seal rings. As Figure 4 shows, the seal interface can be imagined as a very narrow annular gap across which the seal faces are in partial contact. Full solid contact would be ideal from the perspective of avoiding leakage. On the other hand, a pure fluid film—with no solid contact—minimizes frictional forces, wear and heat generation. The design of the seal ring must therefore take into account both aspects, and thus always represents a compromise. This condition is known as mixed friction: the seal faces are in partial contact, yet thanks to lubrication they also are able to slide over each other.

The physical and chemical processes taking place within the sealing gap of a mechanical seal are difficult to describe theoretically. Some processes, such as blistering on seal faces, are not yet completely understood because it is hard to take measurements at the seal interface. The key variables influencing the sealing and frictional characteristics of seal rings are the various...
axial forces, which operate in both the opening and closing directions. As Figure 4 shows, the pressure between the seal faces pushes the seal rings apart, whereas the hydraulic pressure on the rings (Figure 5) pushes them together. The ratio of these forces governs the efficiency of the sealing function and how easily the seal rotates. The closing forces must be slightly higher than the opening forces; otherwise, there is a risk that the gap will open suddenly and the seal will start to leak.

The ratio between the closing forces and the opening forces is described mathematically by the hydraulic balance ratio $K$ (Figure 5):

$$K = \frac{\text{hydraulic loading area}}{\text{sealing interface area}} = \frac{A_2}{A_1}$$  \hspace{1cm} (1)

With the assumption of a linear pressure drop across the sealing interface (Figure 4), the closing and opening forces will balance when $K = 0.5$. In practice, optimum performance is obtained when the value of $K$ lies between 0.6 and 0.9.

The hydraulic balance ratio $K$ is also used to characterize mechanical seals as unbalanced or balanced. Unbalanced mechanical seals have $K > 1$, whereas balanced seals have $K < 1$. Unbalanced seals are expedient for simple operating conditions, such as low pressures and low agitator speeds. Here, the high hydraulic balance ratio, with closing forces dominant, provides good sealing efficiency without thermally overloading the mechanical seal. In more-difficult operating conditions, such as high pressures and high agitator speeds, only balanced mechanical seals can be used.

So far we have ignored the closing force contributed by the springs that form part of every mechanical seal. This force is generally equivalent to a pressure of 1–2 bars. This is important at low operating pressures, but can confidently be neglected at vessel pressures above 10 bars. Nevertheless, even high-pressure mechanical seals require springs to keep them closed while they are unpressurized.

**Barrier fluids**

Another essential factor influencing the function of a mechanical seal is the choice of barrier fluid. This liquid has three main functions: lubrication, cooling and sealing. It must also meet certain secondary conditions, such as compatibility with the product and, if necessary, conformity with the specifications of the U.S. Food and Drug Administration (FDA).

Figure 6 compares barrier fluids used in mixing applications with respect to their suitability for various tasks. It is clear that the demands of lubrication and cooling may conflict. Water cools efficiently, but lubricates poorly, whereas the reverse is true for mineral oils and pure glycerin. A mixture of glycerin and water can be a successful compromise: the glycerin lubricates, while the water phase cools. For this reason, glycerin/water mixtures should always be used if possible. Unfortunately, not all products tolerate a glycerin in-leakage of several milliliters per day, though it is technically possible to collect the leaked barrier fluid and keep it away from the product.

Especially when water or organic solvents are used as barrier fluids, special
cooling measures may be necessary to dissipate the greater frictional heat. Compromises of this kind in the choice of barrier fluid generally shorten the service life of the seal rings.

Materials of construction
Modern seal rings made of SiC, graphite, or SiC/carbon graphite composites can handle nearly all sealing tasks. O-rings are nearly always made of fluorocarbon (FKM/FPM) rubber such as Viton, which withstands a wide range of temperatures and chemical environments. The most demanding requirements for chemical resistance require perfluoroelastomers (FFKM). Most of the other components of mechanical seals are made of stainless steel.

Supply systems
Supply systems ensure that the mechanical seal operates safely and reliably. A mechanical seal is regarded as being technically tight when the pressure in the seal chamber is always higher than the vessel pressure. The supply of seal liquid is thus of primary importance to safety. The seal liquid also lubricates the seal interface. The tasks required of the supply system include:

**Pressure maintenance.** Alternatives for pressure maintenance are continuous flow systems and pressure compensator arrangements (discussed further below).

**Cooling.** The physical processes taking place in the seal interface and at the seal faces are very sensitive to high temperatures. If critical values are exceeded, this may cause localized areas to dry out, resulting in hotspots and greater shear stresses on the surfaces of the seal rings. The sealing function is compromised as soon as the surface structure has been destroyed (blistering). Heat conducted to the seal from the vessel, and generated by friction at the seal interface, must therefore be continuously removed. Continuously operating cooling systems are extremely important for reliable operation. Cooling systems for mechanical seals must be designed so that the seal rings, O-rings and barrier fluid are not thermally overloaded. The weakest link in this chain is usually the barrier fluid, because it evaporates if the temperature of the seal faces is too high. Without the cooling and lubrication provided by the barrier fluid, the seal faces will rapidly suffer damage and drastically reduced service life. Long-standing experience at EKATO indicates that, irrespective of the type of barrier fluid, the temperature should not exceed 80°C.

**Flushing.** In many processes, corrosive or abrasive substances contaminate the surfaces of the seal rings. To protect them, the rings can be flushed with a compatible liquid.

**Emergency supply.** In the event of an unexpected increase in the leakage rate due to damaged seal rings, the normal system may not be able to supply enough barrier fluid to keep the seal rings cooled and lubricated. To maintain the positive pressure difference between the mechanical seal and the vessel, and thus maintain the lubrication function, a backup seal liquid (often water) is circulated through the mechanical seal at a higher flowrate. This allows the reactor to continue operating for a certain time after leakage has increased.

**Seal liquid refill system.** An outstanding characteristic of mechanical seals is their very small leakage rate, even at elevated vessel pressures. A leakage rate of only 20–50 mL/d

---

**FIGURE 7.** This matrix aids the choice of the various modules typically associated with seal-liquid supply systems, according to their suitability for different applications.

**FIGURE 8.** This arrangement makes use of a thermosiphon to circulate and cool the seal fluid without the need for a pump.
can be expected during normal agitator operation at vessel pressures up to 70 bars. Nevertheless, it is advisable to monitor the leakage rate continuously and refill the system automatically when needed. This is especially important in continuous mixing processes.

Figure 7 shows the support systems recommended for various operating conditions.

**Continuous flow systems**

Water cooling systems and circulation pumps are not very popular because the necessary pipework and pumps increase the capital outlay. They also consume water and electricity, and require extra maintenance.

Fortunately, simple sealing tasks do not require these additional elements if we exploit the thermosiphon effect to circulate the seal liquid, and natural convection in the surrounding air for cooling (Figure 8). Hot liquid has a lower density than cold liquid, so it rises into a storage vessel mounted above the seal. Natural cooling of the liquid storage vessel then sets up a circulation through the seal. The storage vessel can also be cooled with a water jacket instead of air. A supply of compressed gas is required to pressurize the storage vessel.

If the thermosiphon effect is insufficient to remove the generated heat quickly enough, the seal liquid must be circulated with a pump. Natural convection cooling with air must also be replaced or supplemented by forced cooling with liquid, for instance cooling coils in the storage vessel.

The resulting forced circulation cooling system (Figure 9) can only operate reli-
ably if it is equipped with suitable monitoring instruments, such as flowmeters and temperature sensors. The most important component in terms of safety is the pressure control valve. This ensures that the pressure in the seal-liquid circuit is always greater than the vessel pressure. The usual arrangement is to set the seal-liquid pressure at a fixed value 10% above that of the maximum vessel pressure.

Also important to safety is an accumulator. If the circulation pumps should fail, for instance following a power failure, the high pressure in the seals is maintained by valves. During this time, the accumulator ensures that the pressure in the seal-liquid circuit remains higher than in the vessel, and also supplies more seal liquid to replenish leakage.

Pressure compensators

An alternative to setting the seal-liquid pressure at a fixed value is to use a pressure compensator. This allows the seal-liquid pressure to follow the vessel pressure. A pressure compensator is a hydraulic cylinder in which a piston acts as a divider between two fluid chambers (Figure 10). The lower face of the piston is subjected to the vessel pressure \( p_B \), while the seal-liquid pressure \( p_S \) acts on the upper face. The area of the lower face \( (A_B) \) is shown by the yellow circle in Figure 10; the upper face has a smaller area \( (A_S) \) because the piston rod occupies some of the top surface, as the red “dougnut” in Figure 10 shows. The force balance is:

\[
p_B \times A_B = p_S \times A_S \tag{2}\]

Because \( A_B/A_S > 1, p_S > p_B \). The area of the piston rod is arranged so that the pressure in the seal liquid is always higher than the vessel pressure by the required differential.

As Figure 3 shows, the lower chamber of the pressure compensator is connected to the headspace of the vessel via the seal flange. The upper chamber is connected to the seal-liquid chamber. This arrangement ensures that the pressure in the seal-liquid chamber automatically follows the vessel pressure (Figure 11).

The inboard pair of seal rings is generally regarded as particularly critical because these rings are directly exposed to the process, and so bear the brunt of corrosion, erosion and high temperatures. Under varying operating conditions, such as those found in batch processes or during commissioning, a pressure compensator can reduce wear on these rings by dropping the seal-liquid pressure to the minimum safe value.

Pressure compensator systems are generally equipped with a manually controlled pump for refilling. An automatic refill system is recommended if there is more than one agitator (Figure 12) to exclude possible errors by operating personnel. Position monitoring of the pressure-compensator piston (Figure 3) provides very sensitive monitoring of the leakage behavior of each individual seal. This enables countermeasures to be started in good time if premature failure of the seal is imminent.

Summary

In most mixing systems, reliable agitator sealing requires a complete mechanical sealing system. As well as the mechanical seal itself, auxiliary equipment is needed to maintain an adequate flow of fluid at the correct temperature and pressure to cool...
and lubricate the seal faces. Careful selection of hydraulic and other components is thus just as important as the reliable design of the mechanical seal itself. The sealing function of the vessel can only be guaranteed and maintained if the complete system is correctly selected, installed and maintained.

When a mixing system is being commissioned, support and training for the equipment operators are very important to allow work to proceed rapidly and without problems. Once the plant is up and running, training and support are often the cornerstones needed to ensure high availability of the complete mixing system.

Edited by Charles Butcher

References

Author
Bernd Reichert is a Senior Mechanical Engineer at EKATO Rühr- und Mischtechnik GmbH (Hohe-Flum-Strasse 37, 79650 Schopfheim, Germany; E-mail: bernd.reichert@ekato.com). He is head of the Sealing Technology group within EKATO’s R&D department. Reichert holds a bachelor’s degree in mechanical engineering from the University of Applied Sciences Konstanz (Germany).

FIGURE 12. This automatic refill system serves 24 mechanical seals