UPSTREAM PUMPING: NEW DEVELOPMENTS IN MECHANICAL SEAL DESIGN

by
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ABSTRACT

Conventional mechanical seals are arranged to prevent leakage from a high pressure source. When leakage occurs, it is expected to be from the high pressure area to the lower pressure surroundings. The basic concept of the upstream pumping seal is that the conventional seal is replaced by a low volume, high pressure "pump"—the upstream pumping seal. This "pump" propels a minute quantity of barrier liquid along the path normally sealed by the mechanical seal and into the product side. Because the product side is at a higher pressure than the barrier liquid, this seal is said to pump "upstream."

INTRODUCTION

There are many different types of mechanical seals and regardless of their differences in appearance, they fit into certain categories. Conventional mechanical seals can be arranged by design characteristics or by positional arrangements (Figure 1). Balanced/unbalanced, rotating head/stationary head and pusher/non-pusher are design classifications, while classification by arrangement addresses orientation and arrangement of the seal(s) regardless of design.

As sealing capabilities of single seals became exhausted, multiple seals soon made their appearance. During the last few years, they have found their way into industries at an increasing rate. API 610 5th Edition recognizes multiple seals as a "double" arrangement and offered a choice between S (single) and D (double) in the five character API seal code. A double seal arrangement was the answer to difficult services—erosive, abrasive slurry, nonlubricating, and gaseous services. Two mechanical seals mounted back-to-back (Figure 2) operated in an artificially created desirable environment for the seal provided by a clean, lubricating pressurized barrier fluid. The life of the seal was basically a function of size, speed and pressure, totally ignoring the sealed product.

Figure 1. Mechanical Seal Classification.

The safety of the environment and long seal life comes with a price tag: a pressurized seal support system is essential. The high pressure barrier fluid ensures that leakage would occur only from the barrier fluid region into the product side and/or from the barrier fluid region into the atmospheric side. API Plan 53 and 54 are present day support systems for such double seal arrangements. It must be noted here that a high pressure system is essential for seal operation. Should a pressure reversal occur, resulting in a pressure in the throat of the seal cavity lower than the pressure between the two seals, the unbalanced seal will "blow" open causing the product to enter the area. With a non-lubricating slurry or abrasive product, a seal failure becomes imminent. This loss of barrier fluid pressure could be caused by:

- loss of pressure source - nitrogen blanket or failure of circulating and pressurizing unit.

Figure 2. Conventional Double Seal Arrangement.
• failure of outboard seal.

Tandem seals are a trend of the present day sealing technology. API 610 recognizes it as ever increasing popularity, and in the 6th edition, introduced the letter "T" in its five character seal code to designate and classify tandem arrangements. Tandem seals consist of two single seals mounted in the same direction (Figure 3) with a secondary neutral fluid at or near atmospheric pressure between the two seals. Tandem seals are utilized for three main reasons:

• Redundancy—as a safety back-up; in the event of a failure of the primary seal, the secondary seal will prevent spillage/leakage into the environment.

• Contain a quench fluid—cryogenic services and services with dissolved solid (caustic, sugar).

• Arrest fugitive emissions—sealing of light hydrocarbons/VOCs.

**UPSTREAM PUMPING**

Upstream pumping is a "hybrid" between a tandem and a double arrangement. In design and concept, it appears like a redundant end face mechanical seal arrangement with a low pressure barrier fluid between the two seals. In function, however, it operates like a double seal. A pumping mechanism in the primary seal generates pressure which results in a minute amount of controlled pumpage from the high pressure barrier region to the high pressure product side. The conventional end face primary seal is replaced by a low volume, high pressure "pump"—the upstream pumping seal. This "pump" propels a minute quantity of barrier liquid along the path normally sealed by the mechanical seal and into the seal cavity. Because the seal cavity is at a higher pressure than the barrier fluid, this seal is said to pump "upstream."

**APPLICATIONS**

In general, complexity of a system is inversely proportional to reliability—the more complex the system, the less reliable. Because external systems are unnecessary with a single seal, it has the highest reliability. Multiple seals are more complex than single seals, and amongst themselves, vary in degree of complexity depending upon double or tandem arrangement. All multiple seals require external systems but the external systems for tandem seals are less complex than double seals; and hence, the overall reliability of tandem sealing system is greater than double sealing system. Indeed a multiple seal system may be less reliable overall because of either:

• the constant contamination of the barrier fluid in a tandem arrangement, or

• the higher level of complexity of the seal support system for a double arrangement.

Moreover, in a double arrangement, it is normally assumed that leakage occurs only from the barrier fluid into the process. Unfortunately, this is not always true. Leakage can occur from the process into the barrier fluid in spite of the pressure difference. Experimental data indicates that this "reverse flow" is an interface phenomenon which is not easily eliminated. It is noteworthy, however, that the upstream pumping seal completely eliminates leakage of the process into the barrier with a seal support system that is at a lower level of complexity, for most services, than the support system for conventional tandem arrangement.

The upstream pumping seal, thus, can be applied for:

• toxic and hazardous

• abrasive and slurty

• products with poor lubricity, and

• high PV services.

The first two categories are usually handled by ANSI pumps with low suction pressure and speeds at either 1800 or 3600 rpm fitted with double mechanical seals and API Plan 53 (pressure reservoir system) or a single mechanical seal and API Plan 32 (external clean flush). In either situation, the upstream pumping seal provides a simpler alternative with controlled low product dilution (0.1 to 16 cc/min).

Products with poor lubricity such as supercritical CO2, ethylene, etc., are usually high pressure services handled by API pumps, and almost always require double seals with complex, redundant seal support systems. At the author's location, work is presently near completion on an upstream pumping seal for high pressure super-critical CO2 service with a significantly simplified seal support system.

The expression "PV" is routinely used by the seal manufacturers and users alike to identify the Pressure-Density limits of sets.
of face material combination in a given fluid. High speed pump applications are usually high "PV" services and the situation is worsened by the use of double seals due to the higher buffer pressure requirement. The high "PV" problem has been plaguing the high speed pump industry for a long time. The upstream pumping seal seems to be the solution the industry has been waiting for, by not requiring a higher barrier fluid pressure than the pressure at the throat of the seal cavity. The pressure component of "PV" is completely eliminated due to its essential non-contacting mode of operation.

FIELD EXPERIENCE

A partial list of successful field installation is shown on Table 1.

PRINCIPLES OF OPERATION

The upstream pumping seal operates on the principle of hydrostatic and hydrodynamic force balances. The seal head with the retainer, springs, and primary ring is mounted in a stationary configuration. The rotating mating ring is spirally grooved. The groove pattern is a series of logarithmic spirals which are recessed. The ungrooved portion of the face above the spiral pattern is called the sealing dam. When pressure is applied, the forces exerted on the seal are hydrostatic and are present when the mating ring is stationary or rotating. Hydrodynamic forces are generated only upon rotation. The spiral groove pattern plays a vital role as, upon rotation, it serves the purpose of a pressure generating system. The spiral groove pattern as shown on Figure 4 rotates in a counter clockwise direction. As the barrier fluid enters the groove, it is induced towards the OD where it meets the resistance of the sealing dam. Pressure is increased causing the flexibly mounted face to lift-off setting the sealing gap. A 'pump-restrictor' principle is at play which results in a non-contacting mode of operation with liquid being pumped from a low pressure region to a high pressure region.

The forces which govern the seal operation are axial, shown graphically in Figure 5. Opening force \( F_0 \) is the sum of the pressure generated by the spiral groove pattern plus the pressure drop across the face and the closing force \( F_C \) is the system pressure acting behind the face plus the spring force. Under ideal conditions, the seal will establish its operating gap creating a pressure distribution as represented in Figure 6. If, as a result of some disturbance, there is a decrease in the sealing gap, the forces within the film considerably increase. Similarly, if the gap increases, there is a reduction of the forces within the film. In both cases, the original gap is quickly restored. Unlike the purely hydrostatic type of seal, which produces the sealing gap by pressure only and is independent of speed, the upstream pumping seal is both hydrostatic and hydrodynamic, thus making it speed and pressure dependent.

EFFECTS ON PRESSURE AND HEAT

Increased pressure in the product side of a pump subjects the primary ring to radial and angular distortions due to the non-uniformly distributed moment acting about its centroid. This type of distortion leads to a convergent fluid film as indicated in Figure 7, which may choke fluid flow across the seal faces. Parallel faces are essential to optimum performance of the seal and a near zero moment can be achieved either by selecting the right geometry and/or using material with a higher modulus of elasticity.

Table 1. Upstream Pumping Seal Installation Experience.

<table>
<thead>
<tr>
<th>Installed at</th>
<th>Seal Size</th>
<th>Process Liquid</th>
<th>Buffer Liquid</th>
<th>Temp (°F)</th>
<th>Pressure (PSIG)</th>
<th>Speed (RPM)</th>
<th>Date Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exxon Chemical</td>
<td>1.625</td>
<td>Sour Water</td>
<td>Water</td>
<td>150 Max</td>
<td>80</td>
<td>1900</td>
<td>12-86</td>
</tr>
<tr>
<td>Shell Oil</td>
<td>1.975</td>
<td>Canodic</td>
<td>Water</td>
<td>150 Max</td>
<td>100 Max</td>
<td>1900</td>
<td>7-87</td>
</tr>
<tr>
<td>Arcadian Chemical</td>
<td>1.975</td>
<td>Canodic</td>
<td>Water</td>
<td>—</td>
<td>—</td>
<td>1900</td>
<td>6-97</td>
</tr>
<tr>
<td>Tosco Axon</td>
<td>1.735</td>
<td>Form Water</td>
<td>Water</td>
<td>160</td>
<td>125</td>
<td>3600</td>
<td>4-88</td>
</tr>
<tr>
<td>Tosco Axon</td>
<td>2.375</td>
<td>Sour Gas</td>
<td>Water</td>
<td>75</td>
<td>70</td>
<td>3600</td>
<td>4-88</td>
</tr>
<tr>
<td>Tosco Axon</td>
<td>3.250</td>
<td>Gas. Products</td>
<td>Water</td>
<td>90</td>
<td>16</td>
<td>1800</td>
<td>4-88</td>
</tr>
<tr>
<td>BASF</td>
<td>1.875</td>
<td>29% Nihle</td>
<td>Water</td>
<td>200</td>
<td>20</td>
<td>3600</td>
<td>3-88</td>
</tr>
<tr>
<td>IBM (Rains For)</td>
<td>1.875</td>
<td>Pyrophos.</td>
<td>Water</td>
<td>140</td>
<td>10</td>
<td>1900</td>
<td>3-88</td>
</tr>
</tbody>
</table>
Seal Performance and Calculations

A simplified analysis for estimating seal performance is as follows:

_Closing Force_: Regardless of seal design and type, the closing force of a seal is a function of the axial hydraulic load and the mechanical loading due to the springs and is represented by Equation (1) (Figure 5).

\[
F_c = \pi P_o (r_o^2 - r_b^2) + \pi P_t (r_b^2 - r_i^2) + F_{so} \tag{1}
\]

_Opening Force_: The arithmetic product of the face area and the pressure profile of the fluid film between the two seal faces generate the force opening.

For conventional mechanical seals, leakage is from the ID to the OD which is represented by a decreasing pressure gradient (Figure 8) represented by Equation (2).

\[
F_o = \pi k (P_o - P_i) (r_o^2 - r_i^2) + \pi P_t (r_b^2 - r_i^2) \tag{2}
\]

where \( k \) represents the pressure gradient. The value of \( k \) can range from 0.0 to 1.0 and is approximately equal to 0.5 for parallel seal faces.

For upstream pumping seals, however, the leakage is from the ID to the OD and the pressure gradient \( k_{dp} \) is increasing from \( P_i \) to \( P_d \) due to the pumping mechanism, and the pressure gradient \( k_{dp} \) is decreasing from \( P_i \) to \( P_d \) due to the sealing dam functioning like a conventional mechanical seal (Figure 9). Both \( k_{dp} \) and \( k_{dp} \) can be assumed to be approximately 0.5 for parallel seal faces. Force opening \( F_{oa} \), thus is given by

\[
F_o = \pi k_{dp} (P_d - P_i) (r_o^2 - r_i^2) + \pi k_{dp} (P_d - P_i) (r_b^2 - r_i^2) + \pi P_t (r_b^2 - r_i^2) + \pi P_t (r_b^2 - r_i^2) \tag{3}
\]

**Figure 7. Pressure and Temperature Effects.**

**Figure 8. Pressure Profile of Conventional Mechanical Seal.**

**Figure 9. Pressure Profile of Upstream Pumping Seal.**

**Force Closing/Force Opening Ratio**: For conventional mechanical seals, in order for the two seal faces to be intimately in contact with one another and operate with zero visible leakage, the force closing \( F_c \) has to be greater than the force opening \( F_o \). Typical \( F_c/F_o \) ratios range from 1.2 to 3.0.

In an upstream pumping seal, however, during dynamic condition, the seal operates with a controlled minute gap. The closing and opening forces must equal one another in order to maintain this constant gap. \( F_c/F_o \) thus, must always equal one. As a result, the net pressure \( P \) on the seal face equals zero

\[
P = (F_c - F_o)/A \tag{4}
\]

where \( A \) equals face area.

**Heat Generation**: Total heat generation of an operating mechanical seal is the sum of frictional heat and heat generated by viscous shear

\[
Q = P V A F + u A t^2 / h \tag{5}
\]

As has been discussed earlier, \( P \) for an upstream pumping seal equals zero which reduces the frictional heat to zero. Consequently, heat generation is only due to viscous shear and, thus, is a function of viscosity \( (u) \), face area \( (A) \), mean surface ve-
locity (V), and operating gap (h). Typical operating gap of the upstream pumping seal varies from 60 to 120 μm which affects the seal heat generation inversely and linearly. It must be pointed out that the total magnitude of the viscous shear heat is very small; so small, in fact, that the heat is dissipated by the rotating and stationary hardware of the seal.

Pumping Rate: While relatively independent of viscosity and specific gravity, the pumping rate basically is a function of size, speed, groove design (angle, depth, number of grooves), and pressure. Computation of pumping rate is beyond the scope of this paper, but some typical rates are illustrated in Figure 10, which range from 0.1 to 16.0 cc/min.

<table>
<thead>
<tr>
<th>Shaft Speed</th>
<th>3600 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Temperature</td>
<td>100.0 Deg F</td>
</tr>
<tr>
<td>Barrier Pressure</td>
<td>0.0 Psig</td>
</tr>
<tr>
<td>Barrier Temperature</td>
<td>100.0 Deg F</td>
</tr>
</tbody>
</table>

![Figure 10. Typical Upstream Pumping Seal Pumping Performance.](image)

**SEAL ARRANGEMENT AND SUPPORT SYSTEM**

A typical upstream pumping seal arrangement is shown in Figures 11 and 12. The inboard seal head is mounted stationary, operating against a spirally grooved rotating mating ring, which is coupled to the sleeve by an axial pin. The O-ring is strategically located for the seal head to have the properties of dual balance (1/1 balance), and the springs are isolated from the pumped product which is desirable for slurry services. The outboard seal is a conventional contacting mechanical seal rotating with the shaft and operating against a stationary mating ring.

Support system for the seal takes the form of a simple reservoir with an auto fill valve connected to the plant water line. The auto fill valve will provide constant replenishment of the barrier fluid which will be consumed at the pumping rate—0.1 to 16.0 cc/min (5 fl oz to 6 gal/day).

A good barrier fluid is a cool, clean lubricating liquid that is compatible with the process liquid. Compatibility is specially important since the barrier fluid will be pumped into the process. Typical barrier fluids are water, alcohol, automatic transmission fluid, and kerosene with a viscosity range of 0.4 to 10.0 centipoise and a vapor pressure less than 5.0 psia.

While the inboard seal generates negligible heat, the outboard seal heat is basically a function of size, speed and spring load. Recommended piping connection depending upon seal heat is as follows:

<table>
<thead>
<tr>
<th>Btu/hr</th>
<th>Piping Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1000</td>
<td>Two connections (inlet and outlet) to the barrier fluid to enhance thermosyphon action</td>
</tr>
<tr>
<td>1000 &amp; above</td>
<td>Some positive means of circulation is recommended</td>
</tr>
</tbody>
</table>

**FEATURES AND ADVANTAGES**

In summary, the upstream pumping seal is a highly sophisticated multiple seal arrangement with the following features:

- Capability of pumping upstream.
- A self-flushing seal face.
- Inside seal is noncontacting, therefore, generating little or no heat.
- Outboard seal has low load which also generates low frictional heat.
- Stationary seal head design.

These features translate to the following advantages:

- Reduced or no buffer pressure requirement.
- Eliminates requirement for conventional bypass from discharge for seal flushing, thereby increasing pump efficiency.
- Elimination of barrier fluid contamination by process.
- Elimination of hangers by abrasive particles due to stationary seal head design.
• Reduced P', therefore
  • reduced heat generation, and
  • reduced flush rate requirement
• Savings on maintenance.
It opens up doors to difficult services with a simple and efficient arrangement.

REFERENCES

ACKNOWLEDGEMENTS
The author wishes to acknowledge Gordon S. Buck and Doug Volden of John Crane Inc.