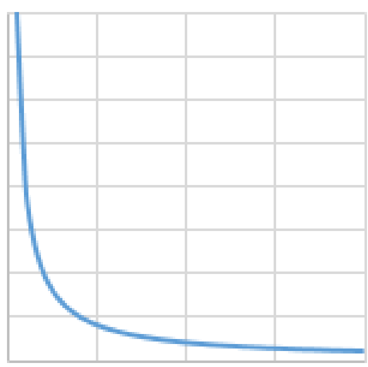
Chapter C14

Hydrodynamic PV limit



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Individual chapters of the Kalsi Seals Handbook are periodically updated. To determine if a newer revision of this chapter exists, please visit www.kalsi.com/seal-handbook.htm.

1. Introduction

During rotary operation, the Kalsi Seal hydroplanes on a thin film of hydrodynamically wedged lubricant, which reduces direct rubbing contact with the shaft and dramatically reduces friction and wear. See Chapter A1 for a description of the principle of operation. For several Kalsi Seal geometries, (Wide Footprint, Axially Constrained, basic Kalsi Seal) the pumping-related hydrodynamic leakage rate during rotation is in about the same range as mechanical face seal leakage. For these Kalsi Seals, the leakage is primarily dependent upon surface speed, and is relatively insensitive to pressure. For the Enhanced Lubrication, Hybrid, and High Film Kalsi Seals, the hydrodynamic leakage at low pressure, moderate temperatures, and moderate to high speeds can be several orders of magnitude higher. The leakage decreases significantly with an increase in lubricant pressure or temperature, or a decrease in speed. In the absence of rotation, the hydrodynamic leakage does not occur.

Hydrodynamic leakage tends to decrease gradually over the long term as running time accumulates, due to minute temperature related changes in lip geometry. In properly implemented seals, ultimate life is dictated by various forms of accumulative damage, such as compression set, abrasive wear, and extrusion damage, which eventually cause the overall leak rate to increase and reach unacceptable levels.

2. Hydrodynamic lubrication limit

Classic hydrodynamic behavior is illustrated in Figure 1. At very slow speeds, boundary lubrication occurs, and seal running torque[1] is relatively high due to asperity contact between the seal and the shaft. As velocity increases, the hydrodynamic activity provides a mixed lubrication regime, and the reduced asperity contact produces reduced torque. In the fully hydrodynamic viscous shear regime, asperity contact is minimal and torque is relatively constant across a wide speed range. In this regime, the torque is primarily related to shearing of the interfacial lubricant film. If the viscosity of the lubricant film remained constant, higher velocity would produce higher torque, but in reality the viscosity thins at higher velocity due to higher seal generated heat, and torque remains relatively insensitive to velocity until the hydrodynamic lubrication PV (pressure x velocity) limit is reached. At the hydrodynamic limit, lubricant viscosity is no longer adequate to prevent asperity contact, and as the film breaks down, torque increases dramatically.

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1 Running torque is the magnitude of the combined seal to shaft rubbing, and lubricant film viscous shearing torques that resist relative rotation between the shaft and the rotary seal.

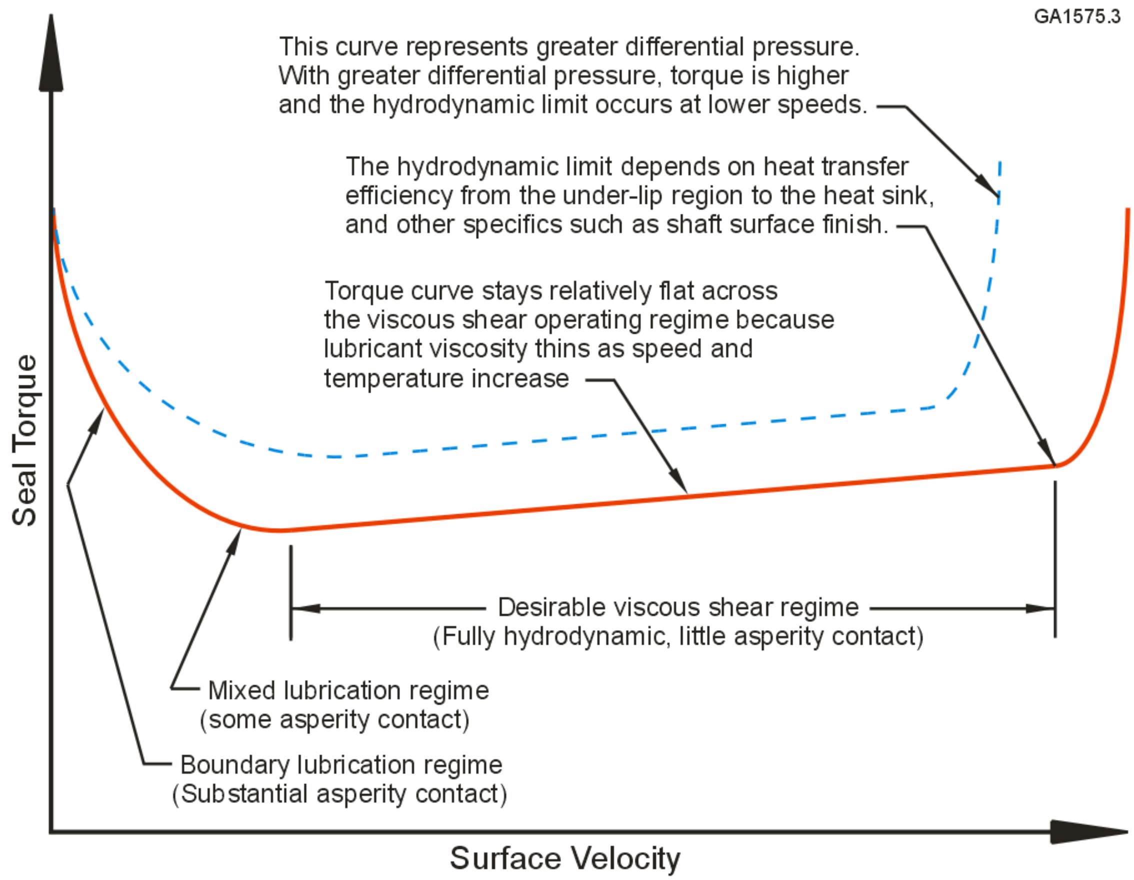

Figure 1

Hydrodynamic Lubrication Regimes

The hydrodynamic limit of a Kalsi Seal is highly application-specific, because it is dependent upon a number of interrelated factors, such as heat transfer efficiency, shaft surface finish, extrusion gap size and corner condition, runout, lubricant viscosity, seal wave pattern, and even material selection.

3. A few words on the fallacy of relying on PV limits

The so called PV (Pressure x Velocity) limit is a much-abused concept which is inherently misleading. Many individuals believe that the “PV limit” is a number that can be divided by pressure to obtain allowable surface speed, or vice-a-versa. This is a delusion.

For example, in our lab we routinely test several types of Kalsi Seals at a pressure of 1,000 psi and a velocity of about 350 ft/minute, which represents a PV of 350,000 psi x ft/minute. If one divides that PV by 10, the result is 35,000. Some might interpret this calculation to mean that the tested Kalsi Seals can handle 35,000 psi at 10 ft/minute, or can handle 35,000 ft/minute at 10 psi. This is a common, but completely erroneous usage of PV.

Even though higher velocities do have negative effects on pressure sealing capability, there are material related pressure limits that cannot be exceeded no matter how slowly a rotary shaft seal is operated. Likewise, even though higher differential pressures do have negative effects on velocity capability, there are velocity limits that cannot be exceeded no matter how low the differential pressure is maintained.

Just as importantly, pressure and velocity limits are highly system dependent. For example, a system with more dynamic shaft runout causes accelerated high pressure extrusion damage, compared to a system with a true running shaft. For another example, a system with good heat transfer characteristics can handle higher speeds, compared to a system with poor heat transfer characteristics.

The PV limit is a relatively undefined concept

It is relatively useless to compare PV values from one manufacturer to another, because of differences in test fixtures, test coupon configurations, testing methodology, evaluation criterion, etc. How does the manufacturer determine the PV limit, and is it described in their published literature? Is the published PV limit based on an applied pressure load using an actual seal, or is it based on a physical load on a test coupon, to simulate a bearing? What are the size and shape of the test specimens used by a given manufacturer, how do they influence the test outcome, and how do they compare to the test specimens used by other manufacturers? How does the configuration of the fixture influence the steady state operating temperature? Is the PV limit based on a reciprocating test or a rotary test?

What is the evaluation criterion? Is the stated PV limit based on the speed at a given pressure or load that causes the material to reach a steady state operating temperature that exceeds the material compounder's published temperature limit for that material—and if so, what was the criterion for setting the material temperature limit, and how does it compare to the criterion other material compounders use? Or is the limit based on material loss, or some other criterion?

From these questions, it should be clear that a published PV limit, without a statement of how it was determined, is relatively useless. It should also be clear that one vendor's published PV limit may not be comparable to another vendor's published PV limit, because of differences in testing and evaluation.

Real world complexities are best understood by prototype testing

The real world of rotary shaft sealing is infinitely more complex than the two variables employed by PV calculations. High pressure can damage rotary seals in different ways than high speed does. A high pressure seal may eventually fail due to accumulative extrusion damage, while a high speed seal may eventually fail due to temperature related compression set. For another example, seal-generated heat increases as speed increases, but at a disproportional rate that is greater than the rate of the speed increase. For yet another example, lubricant viscosity influences both pressure capability and shear related torque and seal generated heat. The list of variables goes on and on.

In real-world applications, heat transfer efficiency and many other factors may differ dramatically from a particular laboratory test. For this reason, the best way to determine the pressure and speed limits and life of rotary seals in your application is to test the actual apparatus in realistic ambient temperature conditions.

4. Typical operating speeds and pressures of Kalsi Seals

Whether testing high or low differential pressure operating conditions, we perform most of our in-house rotary seal testing at surface speeds of 540 ft/minute (2.74 m/s) or less. We have performed several successful extended duration low differential pressure tests of seals having a relatively low hydrodynamic pumping related leak rate at a continuous speed of 860 ft/minute (4.37 m/s). The highest speed our seals are typically exposed to is 1257 ft/minute (6.38 m/s), and this is a low differential pressure application with intermittent rotation, using seals with a relatively high leak rate.

5. Factors that influence speed and pressure capacity

Various factors influence the speed and pressure capacity of a Kalsi-brand rotary seal. Some of the factors can be adjusted to improve both speed and pressure capacity. Other factors improve pressure capacity at the expense of speed capacity, or visa-versa.

Kalsi Seals are much better at dealing with high differential pressure than they are at dealing with high speed. The biggest speed limitation is seal-generated heat—a non-linear effect that increases at a rate that is greater than the increase in speed. The same relatively wide dynamic lip that resists high pressure seal damage and axially acting third body wear also produces heat that limits allowable speed. Beyond a certain speed, it becomes impossible to cool the shaft well enough to keep the sealing material in a satisfactory temperature range. This can lead to premature loss of sealing due to accelerated compression set, or other degradation mechanisms.

Design factors that promote both speed and pressure capacity

Here are several factors that increase both the pressure capacity and the speed capacity of a Kalsi Seal. Several of them reduce seal-generated heat, which allows higher speed operation:

- **Heat transfer efficiency**—The temperatures of the seal and shaft increase due to seal-generated heat. An efficient heat transfer system helps to prevent seal overheating at higher speeds. Cooler seals also have a higher modulus of elasticity, which improves high pressure extrusion resistance.
- **Interfacial lubrication**—As lubricating efficiency increases, asperity contact diminishes, which helps to reduce seal-generated heat. Efficient lubrication helps to prevent seal overheating, and improves high pressure extrusion resistance.
- **Runout**—Reducing shaft runout reduces high pressure extrusion damage, and postpones the time when accumulated temperature-related compression set eliminates sealing contact between the seal and the shaft.
- **Interfacial lubricant shear**—Provided that film thickness is adequate to minimize asperity contact, lower viscosity lubricants have less shear, which helps to reduce seal-generated heat.
- **Extrusion gap clearance**—Provided that heavily loaded rubbing (and related frictional heat) does not occur at the extrusion gap clearance, applications that expose the seal to significant differential pressure will have less interfacial contact pressure and seal-generated heat, and less extrusion damage, with smaller extrusion gaps. With the reduced extrusion gap clearance achievable with floating backup rings, it may in some cases be possible to use a lower modulus seal material, providing lower interfacial contact pressure.

Design factors that influence speed capacity

Here is a non-exhaustive list of factors that influence the speed capacity of a Kalsi Seal:

- **Seal footprint width**—Narrower footprint widths generally result in less footprint area, which typically reduces the amount of seal generated heat by reducing lubricant shear and asperity contact.
- **Interfacial contact pressure**—Lower interfacial contact pressure increases speed capacity. In applications with low differential pressure, interfacial contact pressure can be lowered by reducing the modulus of the seal material, and by reducing the radial compression of the seal. In applications with significant differential pressure, interfacial contact pressure can be lowered by reducing the extrusion gap clearance.
- **Elevated temperature capacity**—Materials that can tolerate elevated temperature while still maintaining useful compression set resistance help to accommodate higher speed operation.

Design factors that influence pressure capacity

Here is a non-exhaustive list of factors that influence the pressure capacity of a Kalsi Seal:

- **Seal footprint width**—In our experience, wider footprint widths with adequate lubrication have less high pressure extrusion damage, while providing extra sacrificial material to accommodate extrusion damage.
- **Avoidance of extrusion gap corner damage**—The condition of the corner between the environment-side groove wall and the bore that defines the extrusion gap is critical. Corner defects, such as nicks and burrs, accelerate high pressure extrusion damage.
- **Seal material**—In general, seals that present a higher modulus material to the extrusion gap clearance have better resistance to high pressure extrusion damage. (Other material factors, beyond modulus, also play a role in high pressure extrusion resistance and overall performance.)