A description of the types of high speed rotary shaft seals in gas turbine engines and the implications for cabin air quality

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This paper discusses some of the background technology of seal designs that may be used on high speed rotating shafts. It concentrates on types that may be found as bearing seals in gas turbine engines on aircraft. Some of the published research covering seal operation and performance in various applications is described. In particular, the implications of the current understanding of seal performance with reference to aircraft cabin air quality is addressed.

Keywords: circumferential seals, labyrinth, leakage, mechanical seals

1. INTRODUCTION

Sealing is a crucial factor in most aspects of our daily lives within our homes and vehicles. Among the hundreds of seals in the average vehicle, modern turbocharged engines include at least one seal that is required to carry out a similar duty to those of interest in this paper; that is, separating the engine air flow from bearing oil. Also in the oil and gas industry, or in a petrochemical processing plant, there are many pumps and compressors with seals that closely resemble those used in gas turbine engines on aircraft.

A key factor with any installation is that the seals impede the progress of fluid. The key word is *impede* (i.e., to delay or prevent), because just about every known seal, including static gaskets, will leak (Fig. 1) [1]. For high integrity static seals it may be an extremely small amount, so small that we call it an “emission” rather than a leak. But even one millilitre per year is still leakage [2].

2. SEAL TYPES

The seals used for the bearings on aero-engine gas turbines are required to operate at high speed and, hence, either a well lubricated seal or one that operates with a clearance is required. The types of seal that are found in this application include: (1) labyrinth seals; (2) circumferential segmented seals; and (3) radial face mechanical seals, also sometimes known as carbon face seals. Each of these will be discussed, in turn, with some known performance information and a comparison of typical applications.

A fundamental assumption involved in the selection of the bearing seals appears to be that, within the compressor stage of the turbine, the air in the gas path will be at a higher pressure than the oil bath in the bearing. This leads to a presumption that any leakage will always be into the bearing housing; i.e., not into the gas path. However, research on seals has shown that some leakage can occur in the opposite direction, and this will be discussed in the following individual sections.

2.1 Labyrinth seals

As implied by the name, a labyrinth seal functions by providing a contorted path to inhibit the leakage. A series of restrictions followed by a clear volume creates expansion of a gas and, hence, reduces the pressure.

A series of labyrinth teeth are arranged to provide a close clearance gap between the rotor and stator components of the machine. A pressure drop will then occur across each gap (Fig. 2a). More complex labyrinth designs are also available (Fig. 2b). The more complex flow paths reduce leakage, but may not be practical for installation and maintenance reasons.
Another factor that influences leakage is grounded in basic gas law theory and, in particular, Dalton’s law of partial pressures. Each individual gas species will endeavour to establish a constant partial pressure. Hence, high pressure air will not actually prevent oil vapour from permeating through the labyrinth against the pressure gradient. This is shown diagrammatically in Fig. 4. In reality, the proportion of fluid that leaks may be very low, but leakage will almost certainly exist. This phenomenon has been thoroughly investigated for many critical static sealing applications, such as electronic component housings and double glazing seals. Anecdotally, it has also been reported to the author for labyrinth seals.

The teeth of the seal are designed to provide a close clearance with the counter-face, and on large rotating machinery the possibility of some shaft instability or other “run-out” must be accommodated, especially during startup, shutdown, and the occurrence of any off-design running condition. For this reason, one part of the labyrinth must be a wearing material. A considerable number of publications have offered calculations of labyrinth seal leakage [3, 4]. The matter is extremely complex because, in addition to calculation of the gas expansion through each stage, the high rotational speed of the shaft has a major effect on the flow pattern [4].

Abradable seals are one way of accomplishing reduced clearances, and they limit the risk of damage to the rotating or stationary member if a rub occurs. Careful design is required to ensure that the clearance is minimized after abrasion has occurred [5]. The abradable component may also be manufactured as a honeycomb material (Fig. 3.) This helps to stabilize the high velocity flow in the seal and assists with preventing instability of the shaft.

All of the variants of the labyrinth seal are still clearance seals; that is, there will always be some leakage flow across the seal from high to low pressure. If the pressure is reversed across the seal during operation of the engine, then oil vapour will flow outwards from the bearing compartment.

Any analysis of this phenomenon would also have to take into account the actual seal arrangement, and for some aero engine bearings this may be quite complex (Fig. 5). The use of an annulus of oil to aid the sealing is also of interest. What happens to this oil film when the engine speed is reduced?

The flow of fluid or vapours through labyrinth seals may also be restricted by incorporating brush seal segments. These are just what they sound like: a series of bristles. These reduce leakage but, as they make contact, they can increase friction and seal wear. They will also generate wear debris, which is not desirable close to the bearing.
2.2 Circumferential seals

Circumferential seals are designed to provide a close fitting ring (a bush) to limit leakage along the shaft. The most common form is a series of segments that are held together to form a bush, typically known as a segmented ring seal (Fig. 6).

The basic types are not designed to provide a controlled clearance. They start as a lightly contacting seal that will bed into a small dynamic clearance and then operate with low-level leakage. They are normally used in situations where some leakage is acceptable, or when there is some auxiliary means of collecting low pressure leakage such as a drain or vent. On the outermost surface is a groove, or some form of retaining device that accepts a garter spring. The spring is in circumferential tension and holds the seal in contact at the butt joints and constrains the segments radially onto the shaft. The more sophisticated designs of these seals have aerostatic features to maintain a small air gap. This will reduce friction and wear while providing better control of the leakage, which may be as low as 3.5 g/s, or approximately 3 L/s [6]. Oil leakage of 30 cm³/s is quoted for industrial gas compressors [7].

2.3 Mechanical seals

Mechanical seals are also referred to as radial face seals or carbon face seals. The most accepted term across a wide range of industries is "mechanical seal", hence it will be used in this paper. Seals of this type are very common across a huge range of applications ranging from high temperature–high pressure seals on water boilers for both conventional and nuclear electricity generating stations, oil refining and petrochemicals to many day-to-day water pumps. A common theme across all these duties is that it is accepted that a single seal will leak a very small amount. The accepted standard for potential leakage within the oil and petrochemical industry is summarized in Fig. 7. Hence, for critical duties where leakage cannot be tolerated, or if continued running after primary seal failure is necessary, a dual seal arrangement will be specified.
A mechanical seal has a pair of radial faces (Fig. 8), one of which is stationary and the other rotates with the shaft. The faces are maintained in close contact by either a series of springs, or a metal bellows in high speed applications. The traditional seal has what are now known as plain faces. They are lapped to a high degree of flatness to provide a good seal. In order to operate at any reasonable speed and provide a long life the faces must be lubricated. It was shown during the early stages of research on such seals that the pressures generated in the lubricating film between the faces can cause the liquid in the film to overcome the pressure gradient and leak, both with and against the pressure gradient [8]. During operation, the faces will also distort due to thermal and pressure effects (Fig. 9). Depending on seal design, this may encourage more lubricant film to penetrate between the seal faces. Some realizations of mechanical seals applied to gas turbine bearings include a direct lubricant feed to the radial seal face. This will again ensure that there is adequate lubricant between the faces, but further increase the volume of oil that will be pumped out to the high pressure (air) side of the seal.

An alternative design of mechanical seal that does not depend on liquid lubrication has become widely used in high speed industrial machinery. What is generally known as a “dry gas seal” generates a thin film of gas between the faces (Fig. 10). Originally introduced as main shaft seals for turbo-compressors, they are now widely used for many applications where there is marginal lubrication. This type of seal is regularly specified for use with hot water close to boiling point and liquid petroleum gas, which is prone to vaporizing in the seal interface. The use of such seals has been proposed for the bearing housings of aero-engine gas turbines [6]. They appear to offer some potential benefits, especially in the situation of reverse pressure, when the oil pressure exceeds the bleed air pressure, and will have the benefit of reduced power consumption in normal operation compared with a conventional mechanical seal.

However, the available illustrations (Fig. 11) [6] suggest that only a single seal would be used, so in the event of a seal failure and reverse pressure there is still the possibility of oil leakage.
3. DISCUSSION

A summary of the various seal types used for gas turbine bearing seals, the typical air leakage through the seal, and the potential for reverse leakage are discussed by Tran and Haselbacher [6]. There are also known mechanisms for each type that would create some fluid transfer against the pressure gradient. In the case of clearance seals, such as labyrinths, this fluid transfer may be caused by partial pressure differentials (cf. Fig. 4). The author is unaware of any work to quantify this effect on clearance seals (in conventional radial face mechanical seals the fluid transfer of the lubricant film is well known and could potentially be quantified).

The dry gas seal design uses a very different régime and runs on a gas film. It would warrant the same comments as the clearance seals, but the gas film is extremely thin, hence any partial pressure effects would be minimal.

In the event of reverse pressure, both labyrinth and circumferential seals are liable to allow leakage in the reverse direction. The volume of leakage would depend on the design of the seal, the clearance and the pressure difference across the seal. The impact of an annular oil film (Fig. 5) during pressure reversals should also be considered.

A conventional mechanical seal is liable to open in the event of reverse pressure, so may have significant leakage, unless this has been taken into account at the design stage. The dry gas seal permits such factors to be taken into consideration at that stage and can be made more resistant to pressure reversals.

Most industrial turbo machines operate in well ventilated environments, but the emissions from the seals are still closely monitored to meet air pollution legislation [1], and many will have a dual seal arrangement. In aero engines, the apparent use of a single seal, with the potential to leak into an enclosed, inhabited space is in sharp contrast to the stringent conditions imposed on sealing applications in other industries. In industrial situations where a faulty seal will create a potentially hazardous condition, then additional precautions are prescribed. Such precautions range from installing a back-up seal to designing seals out of the system by, for instance, the use of gas or magnetic bearings [9].

REFERENCES