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Thermoplastic Labyrinth Seals for Centrifugal Compressors

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THERMOPLASTIC LABYRINTH SEALS
for Centrifugal Compressors
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ABSTRACT
For over 15 years now, the efficiency and reliability of centrifugal compressors have been enhanced by the application of thermoplastic materials to the eye, shaft, and balance piston labyrinth seals. Traditionally these seals have been manufactured from metallic materials and have required relatively large clearances for reliability reasons. By upgrading to carefully selected engineered thermoplastics, the clearances can be reduced without sacrificing reliability. This results in increased compressor efficiency and the added benefit of easier installation. This tutorial will review the design and application of thermoplastic seals as used in centrifugal compressors. The tutorial will not cover in any detail abradable seals (such as babbitt or lead lined), reduced cross-coupling seals, or "other" seals (such as honeycomb, brush, carbon ring, dry gas, etc.).

INTRODUCTION
Labyrinth Seals
A labyrinth seal is a series of annular orifices utilized to seal a region of high pressure from a region of low pressure. These are "clearance seals" and as such, have a certain amount of leakage. In a centrifugal compressor the impeller eye seals, the shaft seals between impellers, and the balance piston seal (FIGURE 1) all are sealing a high pressure area from a low pressure area. These seals can consist of rotating "teeth" sealing against a smooth abradable surface, referred to as tooth on rotor (TOR) designs (FIGURE 2); stationary teeth sealing against a smooth rotating surface (tooth on stator or TOS) (FIGURE 3); or a combination of these (interlocking) (FIGURE 4). TOS and TOR seals are sometimes called "see-through" seals since there is no interlocking of teeth, which would obstruct the view when looking between the sealing surface and the teeth.
The flow of a fluid can be categorized in one of two areas: turbulent flow and laminar flow. By definition, turbulent flow occurs when the local fluid velocities and pressures fluctuate irregularly, in a random manner. The drawing in **FIGURE 5** is an airfoil with turbulent flow behind it. Also, by definition, laminar flow is flow that is not turbulent. The drawing in **FIGURE 6** is of an airfoil with laminar flow passing around it. Turbulent flow involves energy transfer in the fluid and for the case of a labyrinth seal, this turbulence helps to reduce leakage. **FIGURE 7** is a drawing that illustrates the turbulence between teeth in a TOS seal.

[Image 5 - Turbulent Flow as Demonstrated by Airflow over an Airfoil]

[Image 6 - Laminar Flow as Demonstrated by Airflow over an Airfoil]

Labyrinth seals (labyrinths) in centrifugal compressors can have a significant impact on compressor efficiency. In a centrifugal compressor, work is done to increase the gas pressure and this pressure is contained by labyrinth seals throughout the compressor. Gas that leaks past one of these seals needs to be recompressed. Since the gas has already been compressed once, it is hot and therefore needs even more energy to get it back up to pressure. Compressor efficiency can be improved by reducing labyrinth seal leakage.

**Labyrinth Seal Leakage**

The first usable publication on the calculation of the leakage of labyrinth seals was by H. M. Martin (1908). His publication "Labyrinth Packings" presented equations that could be used to estimate leakage through labyrinth seals. Martin’s work was expanded upon by Egli (1935) with his widely referenced paper, "Leakage of Steam Through Labyrinth Seals," which is still used today to estimate labyrinth seal leakage. Twenty-five years later Geza Vermes (1961) further expanded upon Martin’s work by presenting leakage equations for straight, stepped, and combination seals.

At the time of the above referenced work, the impact of seal leakage on overall machine efficiency was considered trivial. It was not until the mid to late 1960s that the impact of labyrinth seal leakage on turbine and compressor efficiency started to become a concern. Around this time, it became clear that labyrinth seals could influence the rotordynamic behavior of a turbomachine. Further work on labyrinth seals then started to concentrate on their impact on rotordynamics; leakage flow concern became secondary once again. Oddly enough, most of the modern-day computer programs that are used to calculate rotordynamic coefficients of labyrinth seals use a version of Martin’s equation to estimate the axial flow through the seal. This is because axial flow impact on the coefficients is trivial; it is the circumferential flow that creates the destabilizing forces. For an excellent discussion on labyrinth seal impacts on rotordynamics, refer to Childs’ book, Turbomachinery Rotordynamics, Phenomena, Modeling, and Analysis (1993).

Additionally, some work has been done on further understanding the leakage of labyrinth seals. Present day labyrinth seal leakage research uses laboratory testing and computational fluid dynamics (CFD) tools to predict seal leakage. This work has resulted in understanding the effect of clearance on leakage (Rhode and Hibbs, 1993), the effect of tooth thickness on leakage (Rhode and Hibbs, 1992), the impact of rounded teeth (Zimmerman, et al., 1994), and rub grooves (Denecke, et al., 2002) on seal performance.
Labyrinth Seals in Centrifugal Compressors

How does seal clearance affect compressor performance? For the purposes of this discussion, we will assume leakage is directly proportional to clearance. We will also assume that the labyrinth end seal, and balance piston seal always provide some degree of compressor’s efficiency loss. In this case, if the leakage could be reduced by 50 percent by reducing the seal clearance by 50 percent, we could appreciate a 2 percentage point increase in efficiency. If all the major compressors in an ethylene plant (cracked gas, propylene, and ethylene compressors) realize a 2 percent efficiency increase this could equate to a $700,000 annual energy savings in a two billion lb/year facility. This example assumes the efficiency gains would be used to reduce power consumption. Quite often however, the gains can be used to allow the plant to produce more product, and this could result in an even greater positive economic impact.

However, the seal clearance cannot just be arbitrarily reduced, because reduced clearance seals can rub and open up, resulting in a negation of the efficiency gain, possible rub related vibration problems, and possible damage to the balance element. Labyrinth seals made from hard, persistent metals that are “as-installed” once installed, can be used because when they rub, during normal transients such as traversing a critical speed, they will “give” and then regain their original “as-installed” geometry. This is the main driving force behind the use of thermoplastic labyrinth seals in centrifugal compressors.

A typical metallic labyrinth seal in the “as-installed,” “during rub,” and “after rub” conditions is illustrated by the drawings in FIGURE 8. Note the seal is installed with clearance to the shaft in the “as-installed” case. The “during rub” drawing depicts the rotor contacting the seal and causing permanent deformation of the seal tooth tip. Therefore, in the “after rub” case the tooth remains deformed and excessive clearance results, leading to increased leakage. As shown, it is possible that galling can take place on the rotating surface as contact between the metallic seal and the rotor occurs. Also during the rub, enough energy may be imparted to the rotor to cause vibration problems and the associated reliability concerns. The drawings in FIGURE 9 depict a similar chain of events with a thermoplastic seal installed. In this case, the “as-installed” clearance is typically tighter than with the metallic seal. During the rub, the tooth deflects, moving with the rotor during this transient. After the rub the tooth regains its original shape and is expected to be deformed over the rotor, and the initially reduced clearance is regained.

Over the years, the authors have seen many seals that have been examined after a typical rub event. In most cases, the seal bore has remained unchanged with no appreciable damage noted to the tooth tip. When clearance is maintained and the rotor rubs against the seal, the as-installed values from years before. This counters the users’ previous experiences with aluminum labyrinth seals where the seals usually show signs of contact and may have been damaged and not replaced. The thermoplastic seal surface. From time to time machines have problems and run for extended periods in a high vibration situation. For these cases, there has been damage to the thermoplastic seals noted. However, based upon most users’ experiences, this damage is significantly less than what would be expected if aluminum seals were installed. Just about every one of these cases also confirms that damage to the rotor does not occur with thermoplastic seals installed.

THERMOPLASTICS

The most common thermoplastics used to manufacture labyrinth seals for centrifugal compressors are TORDION® and PEEK™. Other materials used include Fluorosint® and Vespe® products. All of these products are supplied in various grades where the blending of the final product can influence mechanical properties and chemical compatibility. Most plastics fall into one of two categories. They are either thermosetting plastics or thermoplastics. Thermosets chemically change (crosslink) during processing so that they will never melt again. Thermoplastics are melted and frozen repeatedly. Thermosets can be used as a method again, but thermoplastics, that can be processed by a variety of methods including injection molding, compression molding, and extrusion.

Most of the products that are used for labyrinth seals are