DEVELOPMENT OF A NONCONTACTING SEAL FOR GAS/LIQUID APPLICATIONS USING WAVY FACE TECHNOLOGY

by

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ABSTRACT

A seal has been developed and tested that incorporates a circumferential wave pattern with a sealing dam formed on a SiC face, using a proprietary process. When run against a flat carbon face, laboratory tests show that the wavy seal operates in a noncontacting mode in a gas environment at pressures from zero to 600 psig. Higher gas pressures are achievable but have not been tested yet. Typical face temperature rise is two to six degrees Fahrenheit despite seal size or pressure for speeds from 200 to 3600 rpm. Gas leak rates are one fourth to one half that reported for other noncontacting seals based on grooved face technology at the same operating conditions. Tested gas environments ranged from air and nitrogen to low pressure propane. Testing was done in liquids that included high pressure liquid propane, water, synthetic oil, and crude oil. On high pressure liquid applications, the wavy face seal shows excellent containment of the product. Lab testing shows that the seal successfully contains the sudden introduction of 300 psi liquid propane.

The wavy feature is bidirectional and is less likely to clog than other types of liftoff seal designs that employ some form of grooves in the face. Also, because of the smooth wavy shape, the seal can withstand contact without damage to the carbon face. In all test modes there is insignificant face wear.

The wavy seal is employed as a safety backup to primary seals operating in flashing or nonflashing hydrocarbons. The wavy secondary seal should have a longer life than the primary seal and will prevent excessive leakage to the environment if the primary seal fails. The wavy seal can also be employed as a primary seal in low pressure blowers and as a dual seal with nitrogen or air barrier fluid at a higher pressure than the process. This ensures zero leakage of the product to the environment. Over 60 seals are in the field in a variety of applications.

INTRODUCTION

Over the past several years, there has been a desire by end users of mechanical face seals to simplify the sealing package in many of their applications. Because of the need to provide emission control and safety containment, there is an increased use of dual seals.

With the employment of tandems, or unpressured dual seals, there is a requirement for a support system that consists of a buffer fluid, reservoir, and other equipment associated with such a seal arrangement. This seal arrangement is illustrated in Figure 1. The result is a seal package with near zero emissions and high reliability of containment in case of a primary seal failure [1]. The ability to eliminate this support system, yet maintain the same sealing capability, would result in lower installation costs and maintenance requirements.

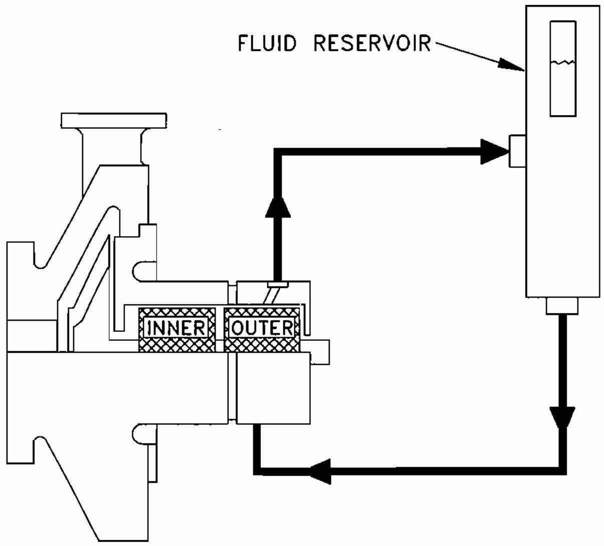

Figure 1. Tandem Seal Arrangement.

Based on this need, the development of both dry running contacting and noncontacting secondary seals have emerged. One use for this type of seal is as a safety backup in hydrocarbon service. On flashing fluids the space between the primary liquid seal and the backup seal is vented to plant flare or other vapor recovery system. If the product to be sealed is a liquid at atmospheric conditions, the leakage from the primary seal is directed to a low point drain. The safety backup seal limits emissions and provides the assurance of containment in case of a primary seal failure. Other possible services include that of a primary seal for blower applications and vertical sump pumps.

Noncontacting seal technology for gas or vapor service uses some types of lift augmentation features on one seal face that produces hydrodynamic load support. This allows the seal faces to be separated by a thin gas film. For the most part, these lift augmentation features are slots or grooves of a specific pattern in one face. This noncontacting mode of operation is also possible by using wavy face technology.

Background

The knowledge of waviness in mechanical face seals has been around for over 20 years. Several investigators sought to quantify and test wavy face seals in the early 1970s [2, 3, 4, 5]. It was examined in great detail analytically by Lebeck [6], who looked at the sources and effects of waviness in mechanical face seals. Subsequent research by Lebeck et, al., [7, 8, 9, 10, 11, 12, 13, 14, 15, 16], showed that waviness can be applied in a very controlled manner in liquid applications to produce a seal with excellent performance giving low leakage and long life. These results show the hydrodynamic load support generated by means of waviness designed into seal faces.

Lebeck shows by mathematical modelling [10, 17] that a wavy face mechanical seal can also be applied to gas seals. The advantage to such a seal is that it can be designed to operate in both gas and liquid environments. Under gas conditions Lebeck's early modelling showed that the load support generated at the seal interface was primarily hydrostatic and not hydrodynamic. Hydrostatic load support is the result of the sealed pressure as it drops from OD to ID (for an outside pressurized seal). Hydrodynamic load support is the result of pressure developed at the seal interface because of dynamic operation. Consequently, it was not known if a wavy face could operate without a pressure differential across the interface. This would have to be resolved by experiment. The zero pressure differential condition is an important operating requirement for a safety backup seal that will be required to operate with little or no pressure for most of the seal's life.

The results for the design, testing, and application of a wavy face gas/liquid seal in gaseous and liquid environments from zero to 600 psi are presented.

DESIGN

Waviness Form

There are many wavy shapes that one could choose for a face pattern. Depending on how that waviness is applied to the face from a manufacturing standpoint, the number of useful shapes becomes limited. The easiest shape to produce is that of a sinusoidal form. This is shown in Figure 2. Because of the need for the wavy face to endure possible contact and therefore wear, it is essential that the wave be incorporated in the harder of the two face materials. In a carbon/silicon carbide mating pair the wave is manufactured into the silicon carbide face.

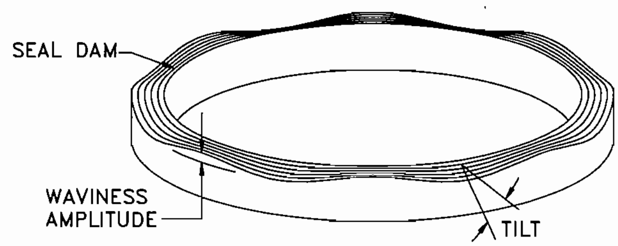

Figure 2. Wavy Face Configuration.

Four important features shown in Figure 2 that are necessary for a successful wavy face noncontacting gas seal design are:

- Waviness amplitude
- Tilt at the wave valleys
- Sealing dam region
- Flatness at the wave peaks

The circumferential converging regions of the waves when mated against a flat face can generate hydrodynamic load support as the gas is compressed between the faces during dynamic operation.

If the waviness is radially constant, no sealing dam is present and the seal is therefore not an optimum shape to restrict leakage. This is the most common form of waviness [18] and is shown in Figure 3. The addition of a seal dam region, as shown in Figure 2, acts to reduce leakage. A natural result of the combination of waviness and a seal dam is the tilt at the valleys of the waves. Tilt enhances hydrostatic load support under conditions of pressure and therefore increases fluid film stiffness. Fluid film stiffness can be characterized by springs between the sealing faces. The stiffer the springs (or film), the more difficult it is to make the faces contact. Flatness at the wave peaks relative to the sealing dam also reduces leakage under both static and dynamic operation by assuring a uniform film thickness for those areas.

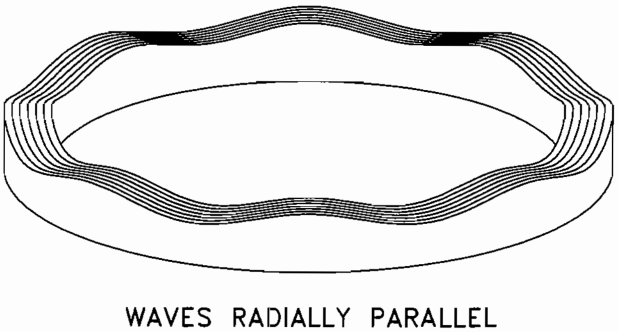

Figure 3. Radially Parallel Waveness.

The shape as shown in Figure 2 underwent design optimization using a recent mathematical model that is the basis for a gas seal design program [19]. This program was used to maximize the gas film stiffness by varying the number of waves, the waviness amplitude, face width, and balance. This was done for three different OD shaft sleeve size seals: 2.375 in, 3.625 in, and 6.000 in. Because film stiffness is lowest for the zero differential pressure case, and therefore the lowest load support available, this operating condition became the basis of the analysis. Results show that as the size of the seal is increased, the number of waves must be increased to maintain maximum gas film stiffness. The 2.375 in seal has four waves, the 3.625 in six waves, and the 6.0 in eight waves. Despite seal size the optimum wave amplitude was found to range between 250 and 450 μin from peak to valley at the OD of the face. Within this range of amplitude, the variation from maximum stiffness is less than 10 percent.

Because this seal operates in the noncontacting mode, distortion caused by thermal effects due to face contact is small. The main contributor to face distortion is pressure. Finite element analysis was also incorporated to design the mating face geometry so that there would be no pressure caused distortion up to the maximum rating of 600 psi. A distortion plot is shown in Figure 4 of the carbon mating face obtained using finite element analysis. The amount of face distortion shown on this plot is one-half light band across the face at 600 psi.

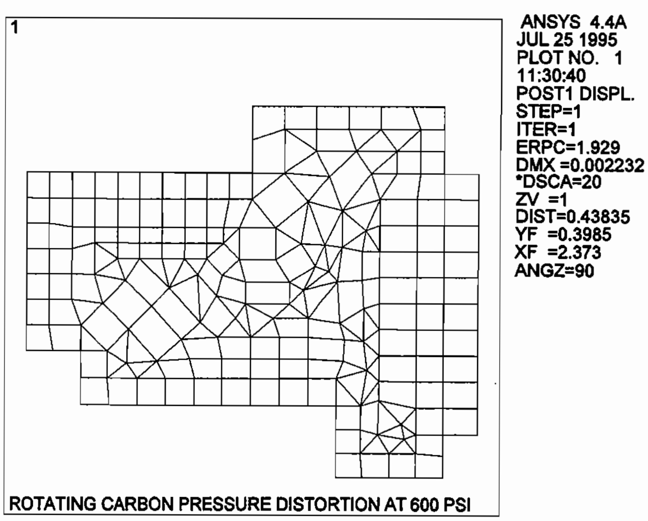

Figure 4. Carbon Face FEA Distortion Plot.

Analysis shows an additional positive feature of the wave shape. The waves promote some circulation of the gas, or liquid if that is the seal fluid. Fluid enters the low pressure valley portion of the wave and moves to the higher pressure region at the top of the wave as illustrated in Figure 5. A small fraction of the flow migrates across the seal dam as leakage while a larger fraction is directed back into the seal chamber. This circulation capability helps to reduce the prospect of clogging which may result from contaminates in the gas or liquid.

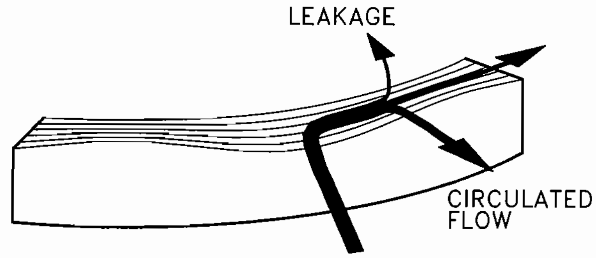

Figure 5. Circulation Effect of Waves

TEST RESULTS

Actual Measured Waviness

After the wavy face design had been optimized, the three different sizes previously mentioned were manufactured using a proprietary process. Once manufactured, the faces were measured for waviness amplitude and flatness of the wave peaks using a precision rotary table with synchronous motor and lever type gage head connected to a data acquisition system. The gage head has an accuracy of ± 4.0 μin and the rotary table of ± 1.0 μin both axial and radially.

Two circumferential measurements were made for each face. The first was at the OD of the face and the second at the sealing dam location as shown in Figure 6. From these two measurements the maximum waviness and flatness of the wave peaks were determined using Fourier analysis of the raw data. An example is given in Figures 7 and 8 of a linear plot of both OD and sealing dam circumferential traces for the 2.375 in seal and the 3.625 in seal. The slight waviness amplitude that is present in Figure 8 at what should be the sealing dam location occurs because the measurement probe was not radially positioned precisely at the dam. In both cases, the magnitudes of the wave and average flatness of the wave peaks were within design specifications.

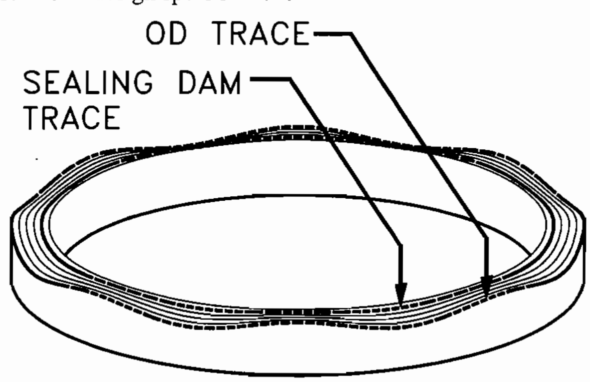

Figure 6. Waviness Trace Locations.

Predicted Performance Based on Actual Measured Waviness

Using the gas seal design program and putting in the wavy shape parameters found from measurement, performance was predicted. The effect of speed on minimum film thickness for two of the designed seals is shown in Figure 9. These results were for the zero pressure case and assuming a combined surface roughness of 10 μin. The combined roughness is given by;

$$\sigma = \sqrt{R_{a_1}^{\,2} + R_{a_2}^{\,2}} \tag{1}$$

where Ra_1 and Ra_2 are the measured roughness for each face. The combined roughness value of 10 μin is high compared to actual measurement and therefore conservative. It can be shown mathematically that there is little probability that any roughness peaks will exceed three standard deviations of this combined roughness [18]. If the two lapped surfaces have a normal distribution of roughness, three standard deviations will give approximately 30 μin for this case. If the film thickness between the two running faces is greater than 30 μin, it would be expected that no contact of the two surfaces would occur. Analysis shows that a speed of only a few hundred rpm's is sufficient to cause the faces to separate 30 μin and run in the noncontact mode, even with no pressure differential.

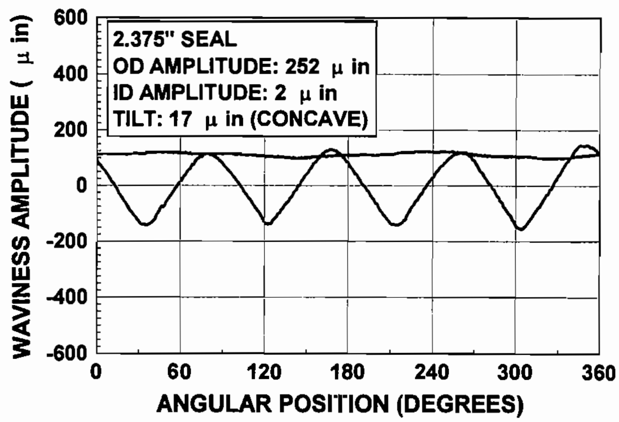

Figure 7. Waviness Trace (2.375 In Seal).

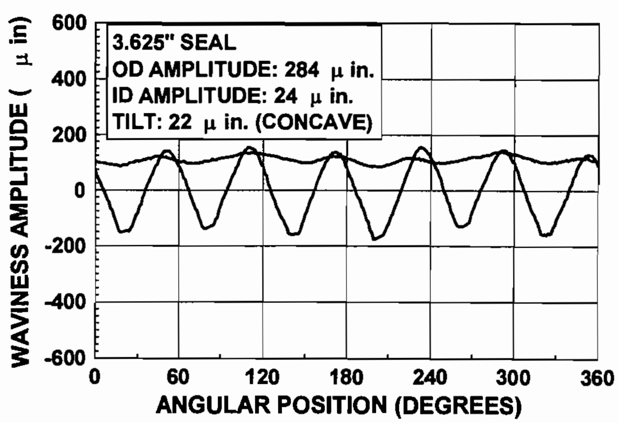

Figure 8. Waviness Trace (3.625 In Seal).

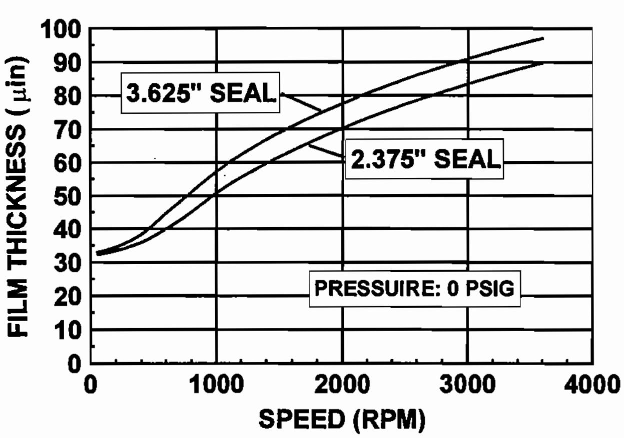

Figure 9. Predicted Film Thickness as Function of Speed.

A plot is given in Figure 10 of predicted leakage as a function of pressure up to 300 psi. These results show that the expected leakage is small and much lower than seals using slots as lift augmentation features.

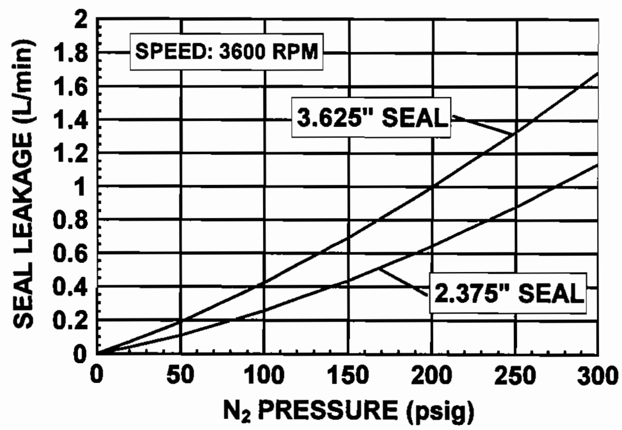

Figure 10. Predicted Leakage as a Function of Pressure.

Test Procedure

The assembly in Figure 11 illustrates the assembly of the wavy face gas/liquid seal in a test stand machine. It incorporates the use of a rotating flat face carbon and a stationary wavy face silicon carbide. Two of these seals were run back to back as shown, and an end plate installed to route gas leakage through a flowmeter. The cavity between the two seals was piped to provide either gas or liquid to the seals. A thermocouple was installed into the back of the stationary face of each seal and another in the seal chamber for temperature measurement. This seal configuration was tested for over one thousand hours under a variety of operating conditions. A list of the tested fluids is shown at Table 1. Some test operating conditions are listed in Table 2.

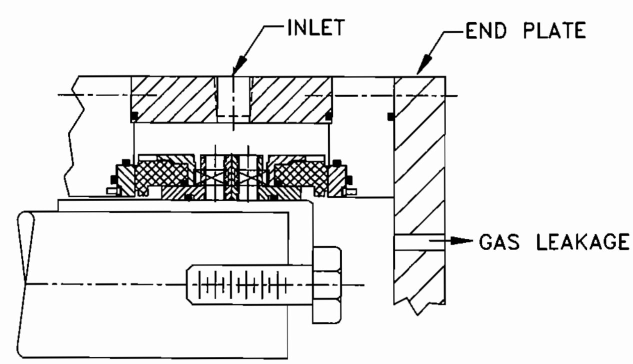

Figure 11. Test Seal Configuration.

Table 1. Tested Fluids.

Air
Nitrogen Gas
Propane Gas
Liquid Propane
ISO 32 Hydraulic Oil
Diesel Fuel
Crude Oil
Water

Table 2. Partial List of Performance Tests.

Test	Fluid	Pressure (psi)	Duration (hrs)	Special Instructions
1	Air	0-5	500	Multiple start/stops during test.
2	Nitrogen	0-600	100	Measure gas leakage as function of pressure
3A	Propane Gas	5-21	17	After 17 hours, flood cavity with diesel at 300 psi for Test 3B
3B	Liquid Diesel	300	3	
4	ISO 32 Oil	600	3	Verify pressure capability in liquid
5A	Propane Gas	5	24	After 24 hours, flood cavity with 300 psi liquid propane for test 5B
5B	Liquid Propane	300	4	Monitor seal emissions
6A	Air / Hydrocarbon Vapor	0-5	144	After 144 hours flood secondary cavity with crude oil for test 6B
6B	Crude Oil	123	5	

Test Results (Gas Conditions)

Initial testing was done in air with zero pressure differential. This is the most severe operating condition due to the lack of hydrostatic load support. These early tests showed that hydrodynamic load support was insufficient and excessive face contact was occurring which was shown by seal face ΔT's (the difference between face and box temperature) of 20° to 40°F. For noncontact operation the ΔT should be on the order of 5°F or less. Several more tests were performed, and in each case post-test face examination showed carbon film transfer to the silicon carbide face. Permanent material transfer decreases the film thickness gap between the faces during operation and causes the faces to contact. At this point, it was not clear if the problem was a question of materials or the design itself. To evaluate the material question, the rotating flat face was changed from carbon to silicon carbide. This test eliminated carbon transfer and allowed for the evaluation of hydrodynamic capability.

Testing a flat face silicon carbide against a wavy face silicon carbide showed excellent operation with only a 2°F ΔT. These results lead to a search for different grades of carbon to identify those that did not produce a film transfer under contact conditions, a condition that can be expected during startup and shutdowns. Also important is the requirement of low wear of both the carbon and silicon carbide face during conditions of forced contact that might be present under severe upset conditions. After more than 1000 hr of testing 23 different grades of carbon, several carbons were identified as successful based on wear and no film transfer. One test that was done to assess potential wear was to run the wavy face seal for 50 hr with no pressure differential and a spring load four times greater than design. This condition forced the faces to operate in contact that produced a seal face ΔT of 9° to 11°F. Post-test seal faces where polished and showed no measurable wear. With these new carbon grades, further gas testing was done.

Thirty-one tests were conducted in gas conditions. The wavy face seal produced a face ΔT of 2° to 6° F despite seal size or pressure for speeds from 200 to 3600 rpm. This low ΔT, along with no measurable post-test face wear, verifies noncontact operation. Also, gas leakage was very low. A plot is depicted in Figure 12 of propane emission in ppm (parts per million) for cavity pressures less than 25 psi and a comparison to predicted. The correlation is extremely good and shows that the calculation of film thickness is quite accurate. As a backup seal to a liquid primary in light hydrocarbon service, the wavy face is an emission-compliant seal since most of vapor disposal system (e.g., flare) back pressures are less than 25 psi.

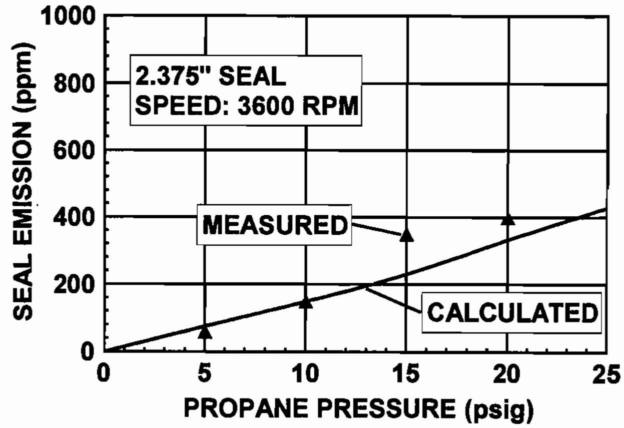

Figure 12. Mearured Propane Emissions.

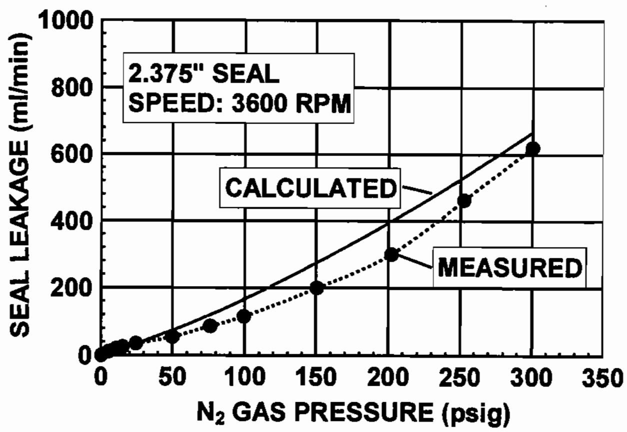

Figure 13. Mearured Nitrogen Leakage.

Measured leakage of nitrogen up to 300 psi and the comparison to predicted is shown in Figure 13. Again, the correlation is quite good based on the actual combined surface roughness measurement of 4.5 μin. This leakage rate is one fourth to one half that of other commercially available noncontacting seals using groove face designs at similar operating conditions.

Test Results (Liquid Conditions Backup Seal Mode)

As part of the test conditions outlined in Table 2, the wavy face gas seal was also subjected to a total of 12 tests operating in various liquids. This is a condition that could occur if the wavy face seal is incorporated as a safety backup seal. Liquid testing generally followed 17 to 144 hr of operation in gas and then subjecting the seal to the sudden introduction of liquid at pressures up to 600 psig. Under 300 psi pressure, liquid propane conditions the wavy face seal contained the product. Although emission levels were roughly 10,000 ppm, there was no visible vapor present.

When oil was used, leakage under static pressure conditions up to 600 psi was limited to only a weep. During dynamic operation, leakage for the 2.375 in seal was about two cc/min at 600 psi using an ISO 32 oil. This leakage will vary depending on the sealed pressure, oil viscosity, and seal size. After all liquid testing was done, post-test face condition showed no measurable wear or damage.

Based on test conditions and results, the operating envelope for the wavy face gas/liquid seal is presented in Table 3.

Table 3. Wavy Face Gas/Liquid Seal Operating Envelope.

Fluid	Operating Pressure
Gas/Vapor	600 psig
Liquid Containment	600 psig
Surface Speed	5 to 100 ft/sec
Pump Operating Temperature	400°F Max.
Specific Gravity	Liquid Backup - .45 Min.
Shaft Sizes	1" to 6"

FIELD APPLICATIONS

Backup Seal Applications

Sixty wavy face seals designed for use as a safety backup to a primary liquid seal, as shown in Figure 14, were installed in a European refinery. Pumped products include propane, ethane/methane, butane, heavy naphtha, propylene, and some combinations of the previous. Product pressures range from 60 psig to 400 psig and shaft sleeve sizes from 2.0 in to 3.625 in. One pump operating in 400 psig ethane/methane experienced an upset that caused the primary seal to fail. A 2.375 in wavy face backup seal successfully contained the product with no sign of leakage for approximately three hours of additional operation until a shutdown could be done. Inspection of the backup seal faces showed no distress or wear.

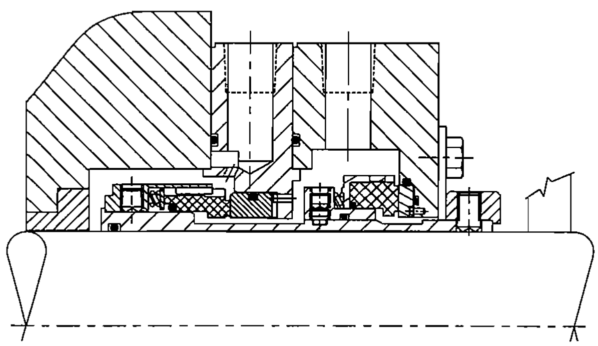

Figure 14. Backup Seal Arrangement.

Another seal (3.625 in) is also running successfully as a backup in propane service in a middle east refinery since June 1995. And in another middle east gas oil separation plant a 6.000 in backup seal has been running without problems in a crude oil booster pump since July 1995.

It has been observed that because the wavy face backup seal is noncontacting, it does not introduce additional heat to the primary seal. This problem could be present with a contacting type seal under certain operating conditions. This has been of benefit with applications in light hydrocarbons where the vapor margin for the primary seal has been small, and any additional increase in face temperature could cause flashing of the product.

Centrifuge and High Speed Mixer Seal Applications

The wavy face seal has also been configured to operate as a pressurized double seal in the centrifuge application shown in Figure 15. This is a 6.000 in seal running at speeds between 20 and 1080 rpm. In this configuration, a nitrogen barrier gas is supplied between the seals at a pressure that is slightly above the product pressure. With this arrangement, zero leakage of the product to the environment is assured.

In a mixer application, the product is at a vacuum and the wavy face seal functions as the primary seal. This is shown in Figure 16. Here ambient air provides a pressure differential across the seal.

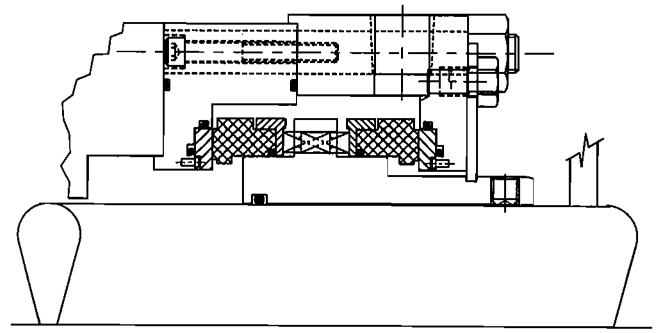

Figure 15. Double Seal (Centrifuge Application).

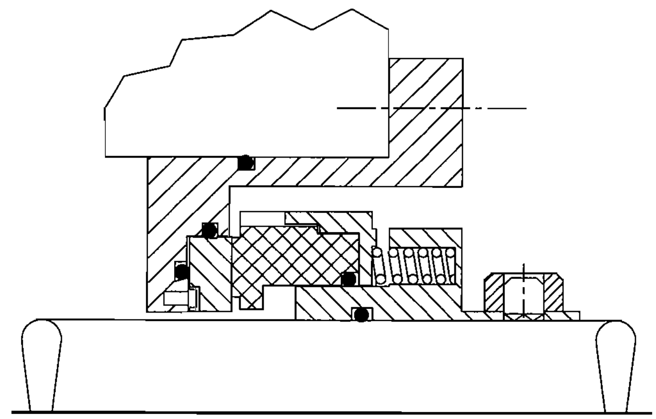

Figure 16. Single Seal (Mixer Application).

Leakage of air into the product is expected to be less than 15 ml/min under highest vacuum conditions for this 6.000 in seal.

Other applications being explored for this seal are as a primary seal in low pressure blowers and vertical sump pumps.

CONCLUSIONS

The wavy face seal has been shown to operate in the noncontact mode for a wide range of seal sizes in air, nitrogen, and propane gas at a zero pressure differential. Verification was by low ΔT and zero wear. This confirms the hydrodynamic feature of the waves and the unnecessary reliance on hydrostatic load support for adequate film stiffness. It also operates in the noncontact mode for gas pressures to 600 psi.

Numerical studies were preformed using various slotted and spiral groove face geometries. Results show that given a comparable film thickness, the wavy face seal cannot generate the same amount of film stiffness under gas conditions. However, test results show the wavy shape can tolerate a great deal of face contact that may occur during severe upset conditions. The smooth wave shape may present a less aggressive contact situation than slotted faces.

The wavy face seal has been shown to operate as a backup seal in liquids with successful containment up to 600 psi under dynamic conditions. Static leakage at full pressure is only a weep.

For low pressure propane gas conditions, below 25 psi, the seal has been shown to comply with emission limits of 1000 ppm.

Leakage rates on nitrogen are one fourth to one half that of other slotted type noncontacting seals.

The wavy shape is less likely to clog from contaminates as compared to slotted faces because of a natural circulation back into the seal chamber that occurs during operation.

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