Brush Seal Blow Down

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Abstract

The blow-down phenomenon exhibited, at varying levels, by all brush seals is examined. Static leakage and torque test data is used to demonstrate the typical magnitude of the phenomenon. Leakage data from a seal at varying clearances over a wide range of pressure drops and pressure ratios identifies a strong relationship with blow down to the pressure drop across the seal. The same seal was then tested with the bristle pack glued solid. This enabled discharge coefficients to be extracted and a formula for the physical blow down to be derived. Development of a finite element model of a brush seal pack with pressure loading highlights how different physical parameters can effect the magnitude of the blow-down.

Introduction

Ever since Cross tested their first brush seals in the 1970's it has been evident that all brush seals tend to "Blow Down" to some extent. The work that we did in the 1990's on introducing brush seals into the Power Generation Industry indicated that soft brush seals with large fence heights tend to blow down more.

This paper presents some test data from a typical brush seal that highlights the "Blow Down" phenomenon. The data is presented in a number of different ways to illustrate the driving forces that lead to the "Blow Down".

A further development of the Finite Element Analysis brush seal model is presented that demonstrates how some of the main characteristics of the seal can affect the blow down. This model is a development of the one presented in 2002[1], and utilizes 3D elements with true bristle to bristle and bristle to back plate contact with axial pressure loading.

Experimental Test Data

The data presented in this paper has been gathered on two of the dedicated Brush Seal test rigs at Cross. All the leakage data was gathered on our 5.1" diameter back pressure rig. The torque data was collected from our 5.1" dynamic ambient rig; both rigs were described in our 2001 paper[2]. All testing has been performed with very slow or no rotation, we have performed blow down tests on the high speed dynamic rigs and have found that the accuracy of the data can be compromised by seal wear. Because of this it was decided to only present the static data in this paper.

Brush seal blow down can be demonstrated effectively in two ways. The first is the reduction in effective clearance with increasing pressure drop when testing at clearance conditions; this effect is shown in the graph in Figure 1.
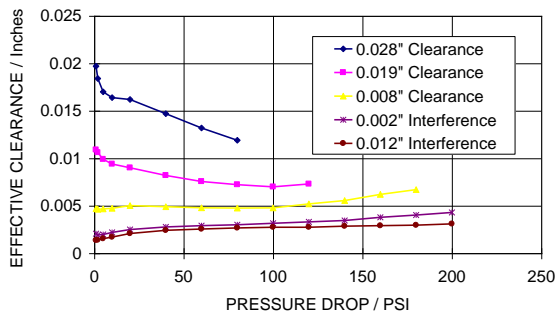
Figure 1 Typical blow down data

The second way that blow down can be seen is via torque test data. The graph shown in Figure 2 shows how the torque characteristics change with pressure drop and clearance change.
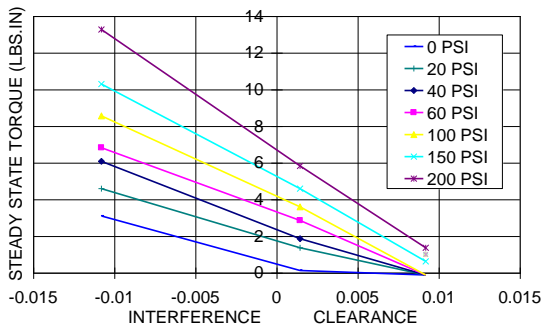

Figure 2 Typical Torque Test Data

The torque test data is very interesting because it tells us a great deal about the blow down phenomenon. The first thing that can be seen is that with interference and increasing pressure drop the torque still increases. The second thing to notice is that at the higher pressure drops the lines are linear with clearance to interference changes. These two relationships indicate that the blow down takes place weather there is clearance present or not, if there is no clearance the bristles just push harder on the rotor. The fact that the lines are linear with changes from interference to clearance indicates that the same forces are present on the bristle pack weather it is tested at a clearance or an interference condition. This tends to indicate that the flow of gas passing under the bristles at clearance conditions has little impact on the blow down and that the pressure drop drives the blow down across the seal compacting the bristle pack.

We decided that the best way to demonstrate brush seal blow down was to leakage test a seal at a range of

clearances and interferences in the back pressure rig, at a wide range of pressure ratios and then to repeat the tests on the same seal but with the bristle pack glued up solid with an anaerobic low viscosity "super glue". This solid brush seal was unable to blow down but should present the same friction parameters to the air passing over it.

Back Pressure Testing Typical Seal

The data shown below in Figures 3 and 4 show how the blow down characteristics of a typical brush seal are effected by the pressure drop and pressure ratio across them. This data was gathered by testing the seal at two clearance conditions at pressure drops ranging from 1 psig to 200 psig with downstream conditions of ambient, 50psig, 100psig, 150psig and 200psig. All the data shown is effective clearance. The upper set of lines on both graphs is at 0.0194" radial clearance with the lower set at 0.0089" clearance.
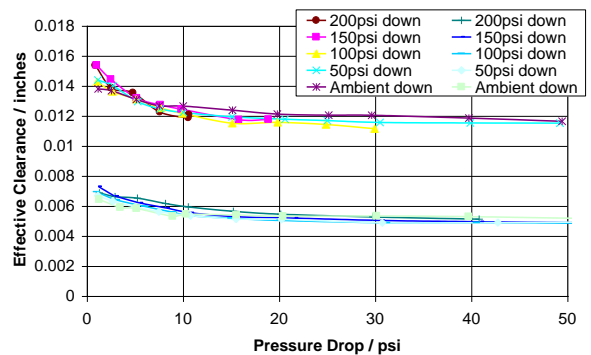

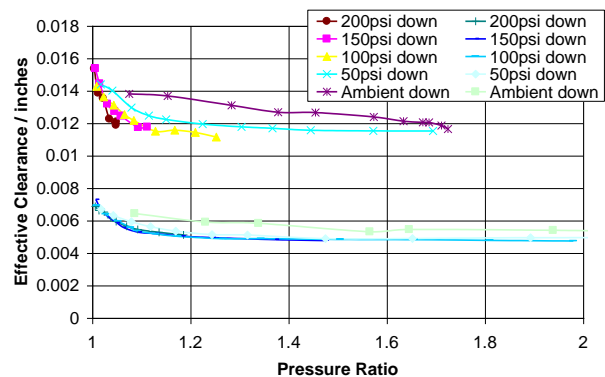Figure 3 Effective Clearance against Pressure Drop

Figure 4 Effective Clearance against Pressure Ratio

Figures 3 and 4 above have both had the x-axis truncated to better illustrate the issues. It would appear

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clear that the effective clearance is related closer to the pressure drop than the pressure ratio.

Back Pressure Testing the Glued up Seal

The same seal that was tested for the data in Figures 3 and 4 was then glued up using a low viscosity anaerobic super glue. The seal was fitted on a test rotor to do this so the bore size was at a slightly different diameter then when originally tested. The seal was tested in exactly the same way as before and the data is shown in Figures 5 and 6. The upper lines are at a clearance of 0.020" with the lower ones at 0.0095".
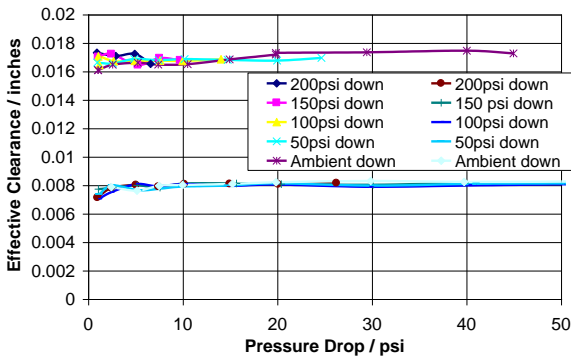

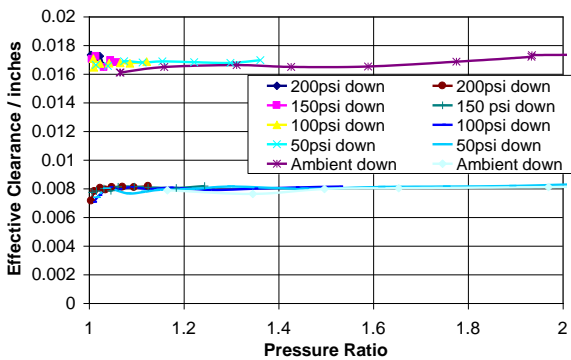Figure 5 Effective Clearance against Pressure Drop

Figure 6 Effective Clearance against Pressure Ratio

With the solid seal we see no blow down and the effective clearance is fairly constant with changes in pressure drop and pressure ratio. Because we have accurately measured sizes it is easily possible to back out a discharge coefficient from the above data. The effective clearance function assumes a discharge coefficient of 1 so by simply dividing the effective clearance value by the actual clearance gives the discharge coefficient. The discharge coefficient is plotted against pressure drop in Figure 7. The coefficient appears to increase slightly with pressure drop. For simplicity all the data at different back

pressures for the same clearance is plotted with the same symbol.
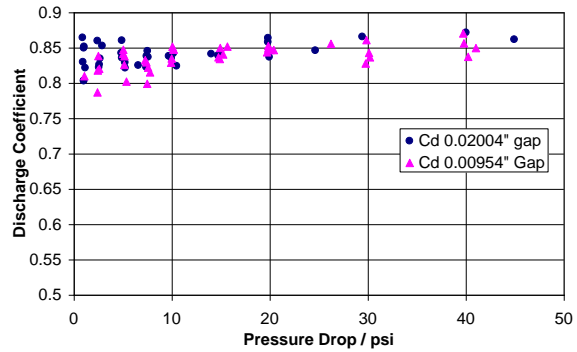

Figure 7 Discharge Coefficient against Pressure Drop

In order to better assess how the Cd is affected by the fluid properties it was plotted against Reynolds Number. In the calculation of the Reynolds Number the velocity was calculated from the pressure ratio with a maximum possible value of the speed of sound. For the length parameter it was decided to use the radial gap value. This data is plotted below in Figure 8.
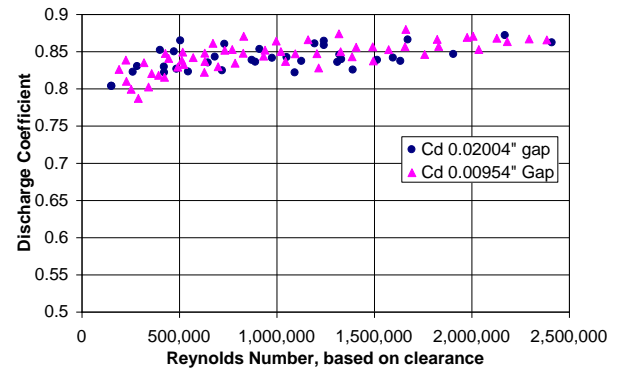

Figure 8 Cd against Reynolds Number

There is clearly a relationship with the Cd increasing with Reynolds Number, however this is quite a small change and for most conditions it would appear acceptable to use a Cd = 0.85

Calculation of Physical Blow Down

The data indicates that if a seal does not blow down at all, that the increase in leakage through the gap between the rotor and bristle tips typically has a Cd of 0.85. We can now use this value to calculate the physical blow down values that brush seal have.

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To enable accurate blow down calculations we need to know the basic leakage that the seal has at a line on line condition. In practice this means leakage testing the seal with a rotor that gives a small interference, typically less than half the wire diameter. Thus to calculate the physical blow down we can use the following formulae:-

$$ BD = C - \frac{(EffCl1 - EffCl2)}{Cd} $$

BD = Physical Blow Down
C = Build Clearance between bristle tips and rotor
EffCl1 = Effective clearance at clearance C
EffCl2 = Effective Clearance at line on line
Cd = Discharge Coefficient = 0.85

Figure 9 below shows the effective clearance data for the seal testing in figures 3 and 4 but with a small interference of 0.0002".
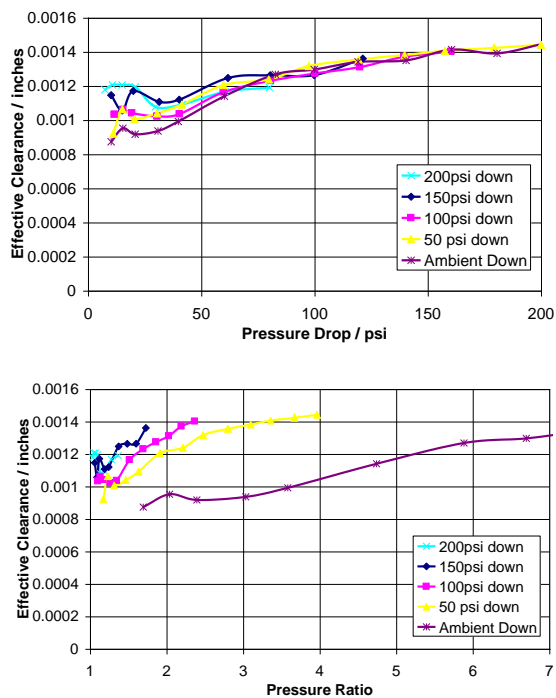

Figure 9. Line on Line Leakage Data

From the data shown in figure 9 it is again apparent that the basic sealing performance of a seal is governed by the pressure drop and not the pressure ratio. We can quite easily fit a curve to the mean of the pressure drop data and then use this in the calculation of the physical blow down. This has been performed and the data is shown in Figure 10.
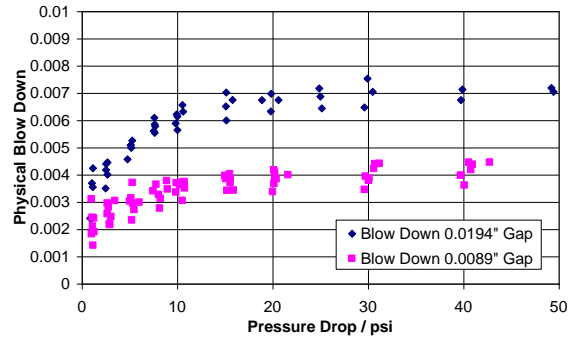

Figure 10 Calculated Physical Blow Down

The data shown above in Figure 10 is interesting in many ways; firstly up to about 15psi the blow down appears linear with pressure drop. Above 15psi the blow down remains fairly constant. If we now focus on the two different levels of blow down given by the different build clearance this, muddies the water slightly as it is apparent that the level and rate of blow down is a function of this initial gap.

In order to better understand how the blow down takes place we have plotted the calculated physical blow down against the $0.5\rho V^2$ term. The velocity has been calculated from the pressure ratio with a maximum velocity equal to the speed of sound. This data is shown below in Figure 11.
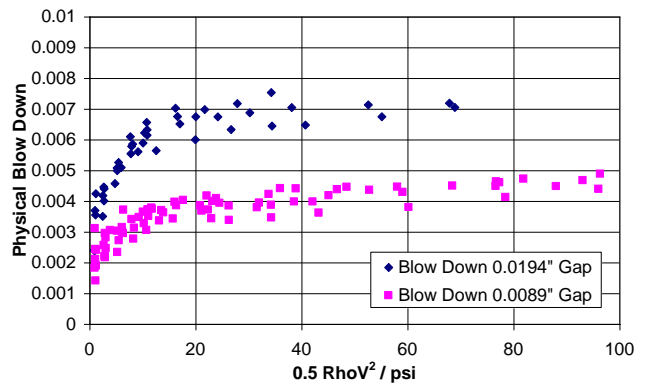

Figure 11 Physical Blow Down against $0.5\rho V^2$

As expected the Figure 11 data is very similar to the pressure drop data. The velocity term used is the maximum velocity present between the rotor and bristle tips, in reality this velocity will vary from the front to the back of the bristle pack.

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Factors that affect the Blow Down

From what we have seen it is apparent that the blow down function is complex. The torque test data indicates clearly that it is pressure drop related, as does the calculated physical blow down. The reality is that there are two main factors that contribute to the blow down, the first is the aerodynamic forces acting under the tips of the bristles, the second is the axial compression of the bristle pack by the pressure drop across it. For many years, as brush seal manufacturers, we have been aware that as you compress the bristle pack axially, during manufacture, the bristle angle decreases and the bristle tips move radially inwards. This happens because as the bristle pack is compressed it tries to take up the smallest axial space, if the bristle angle decreases each bristle takes up less circumferential space, so less axial space is required. There are clearly forces that resist this blow down motion, these are made up of the three following factors:-
1) Friction between the back rows of bristles and the backing plate ring.
2) Friction between adjacent bristles.
3) The spring resistance force of the bristle.

The spring resistance force of individual bristles is easy to calculate using simple beam theory, friction between adjacent bristles is likely to be small as the relative motion will be low. Friction between the bristles and back plate appears to have a very strong influence on the blow down. This is very strongly influenced by the back plate design and the style and effectiveness of any pressure balancing features.

Due to the complexity of the problem we felt that the only way to analyse it with sufficient accuracy was to build a Finite Element Model to simulate the bristle pack.

Finite Element Model

The finite element model used is a development of the one we presented in 2002 using the commercial code Adina. This model has now been expanded to 9 staggered layers. The parametric input routine allows changes in wire diameter, bristle angle, bristle free length, bristle spacing, fence height, bristle to rotor clearance, back plate style and coefficient of friction. The 3d contact surfaces between adjacent bristles allow any part of adjacent bristles to touch each other; the friction vales can be independently set for bristle-to-bristle, bristle to rotor and bristle to back plate contact. We have again used the master slave boundary conditions on the last and first bristle on rows 1,3,5,7

and 9. We feel that this boundary condition best simulates the true bristle behaviour of a complete brush seal. Two views of the model are shown in figure 12.
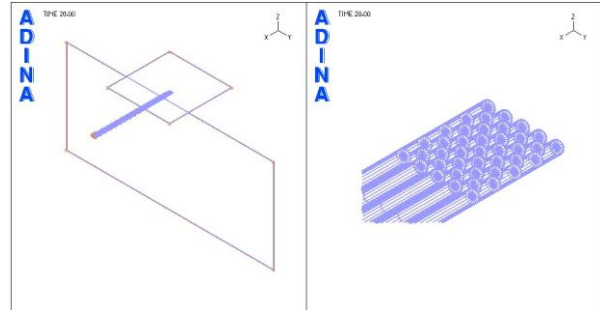

Figure 12. 9 Layer Bristle Model.

Loading in the Model

When we previously presented this model the loading we had in place was to simulate a radial closure between the bristle tips and the rotor. In this paper we have chosen to simulate the blow down so the loading clearly needs to change. We feel that there are two main factors that lead to blow down:-
1). The forces exerted on the tips of the bristles as the fluid expands from the high pressure to low pressure zone.
2). The axial compression of the pack by the pressure drop across it.
In order to accurately model the forces in 1) we need to know the pressure distribution under the bristle tips, we have carried out this sort of measurement and other people have also published data [3,4&5]. However for this paper we are just going to examine the effects from 2). This axial compression is present weather the seal is running with a clearance or interference and we have been unable to find any previously published data on this aspect of seal performance.
The actual pressure loading on the bristle pack is complex, there is a high pressure up stream of the seal, there is a pressure distribution through the pack and then there is the pressure distribution down the back of the last row of bristles. We have simplified this in two stages; the first stage is just to take the up stream pressure on the front row and the pressure distribution down the back of the last row. The second stage of this is to then take the last row pressure distribution away from the up stream pressure to leave the net pressure distribution on the bristle pack, applied to the front row of bristles. This is illustrated in figure 13.
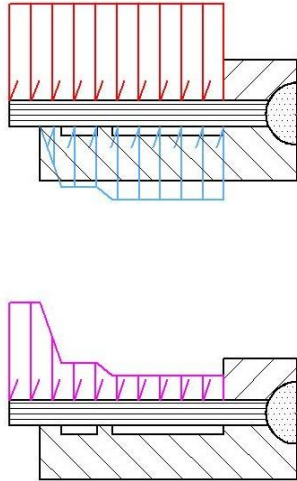
Figure 13. Bristle Pack Loading.

The pressure loading applied to the front half of the first layer of bristles is defined in the model by a spatial function. This function is easy to change to allow for different styles of back plate pressure balance features. The spatial function applies the correct overall pressure drop across the whole of the bristle pack and the rest is sorted out with the contact analysis, there is ultimately no need to know the pressure drop across each layer.

Standard Model Conditions

The model was initially constructed with the following standard conditions:-

Wire Diameter = 0.0056”
Bristle Free Length = 1.000”
Bristle Angle = 45°
Fence Height = 0.1”
Tip to Rotor Gap = 0.020”
Bristle to Bristle gap = 0.00005”
μ bristle to bristle = 0.2
μ bristle to back plate = 0.28
μ bristle to rotor = 0.28
Back plate style was ideal pressure balancing.
Pressure drop from 0 to 50 psi

The model was run with the above standard conditions that are quite typical of a power generation brush seal. Some views of the output are shown in figure 14.
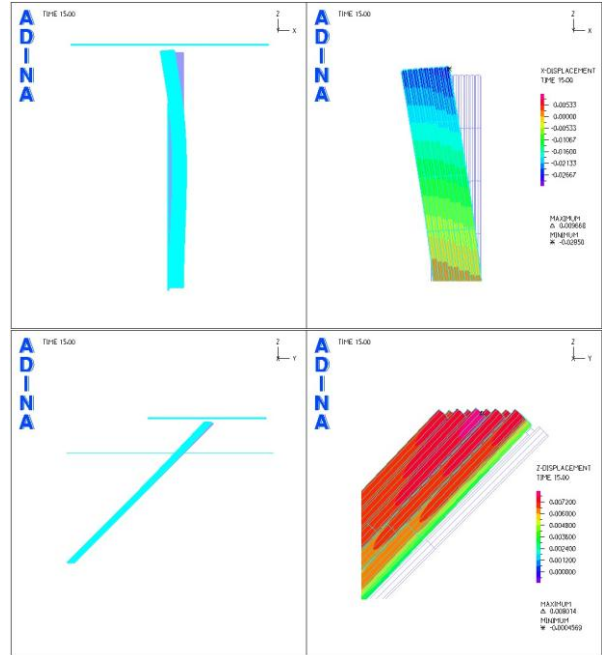

Figure 14 Deflected Bristle Shape.

We decided that it would be good to investigate the effects of the following factors:-
  1)   Friction
  2)   Back Plate pressure balance style
  3)   Bristle angle
  4)   Fence height
The above factors were varied in isolation with all other details as per the standard conditions stated above, the results of varying these factors are shown in figures 15 through 18.

 All charts are plots of blow down against pressure drop, with the blow down taken from the tip of a bristle in the front row.
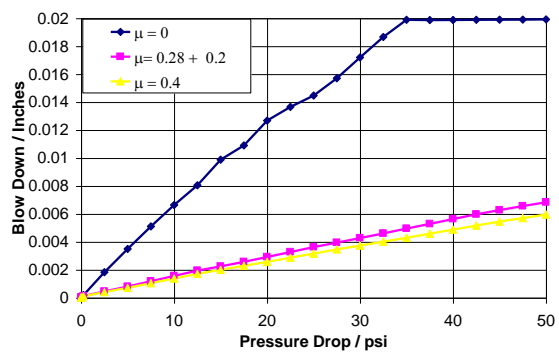

Figure 15 Effects of Friction

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Figure 15 shows us how strongly the blow down is governed by the coefficient of friction. The standard values of 0.2 for bristle-to-bristle contact and 0.28 for all other contact were selected after running many tests using bristles and other geometry.

With the standard settings we see a blow down of about 0.007" at 50 psi, removing the friction completely sees the seal blow down the full 0.020" at 35psi. Increasing the friction to 0.4 on all surfaces resulted in a reduction of the blow down to 0.006" at 50psi.
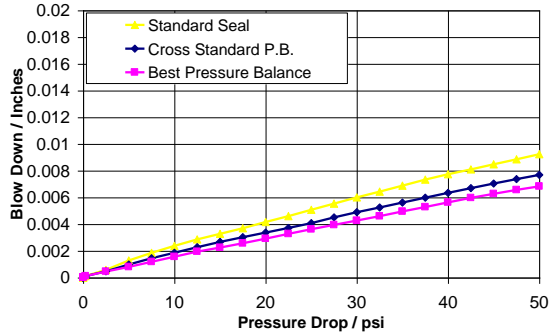

Figure 16. Back Plate Style Effects

The effects of the back plate style are somewhat unexpected. The best pressure balance style is one that is fed via feed holes from the upstream pressure, and our experience is that these seals blow down the most. The standard Cross multi-pocket pressure balancing shows slightly greater blow-down, this is due to there being a greater axial compressing force on the bristle pack. The standard seal with no pressure balance features appears to blow down slightly more, again this is primarily due to the increased axial compression forces due to the lack of pressure balancing. It must be remembered that we are not looking at the whole of the blow-down in this model, we are only looking at the part from the axial compression of the pack and we have not taken into account the aerodynamic forces under the bristle tips. With improved pressure balancing we are likely to see far greater blow-down from these aerodynamic forces, as there will be less friction between the back plate and the bristles.
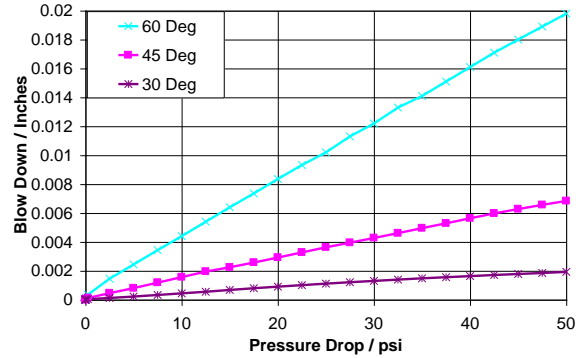

Figure 17. Bristle Angle Effects

From the data plotted in figure 17 it is evident that the bristle angle has a dramatic effect on the blow-down. Stephen and Hogg have noted before this effect in their recent paper[6]. As the bristle angle is reduced so the blow-down is also reduced. Most brush seals are built with a nominal 45 deg angle and it is very clear that the blow down can be increased by a factor of 3 by increasing the angle up to 60 degrees or it can be reduced by a factor of 3 if the angle is reduced to 30 degrees. Clearly good manufacturing control on bristle angle is required to obtain consistent blow-down.
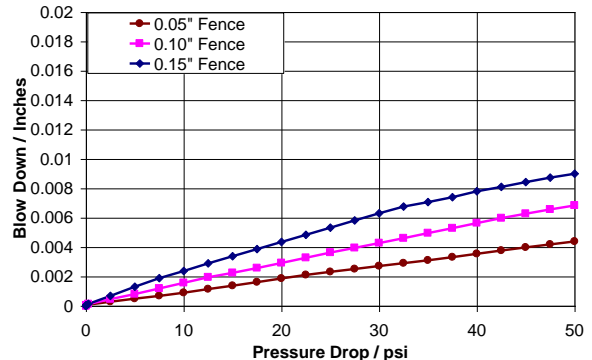

Figure 18. Fence Height Effects

The fence height effects are pretty much as expected, as the fence height is increased so is the total area exposed to the axial clamping forces. It is however not a linear relationship, halving the fence height to 0.050" results in a reduction in blow-down from 0.007" to 0.0043". Increasing the fence height to 0.15" increases the blow-down to 0.009"

Discussion on Model Results

The first thing that must be appreciated is that the models are predicting blow-down purely from the axial compression of the bristle pack, there are no aerodynamic forces under the bristle tips adding to this blow-down. The models appear to correctly model the effects of friction, bristle angle and fence height changes, the back plate configuration gave some initially surprising results. We are continuing to develop the model and will shortly be adding in the aerodynamic bristle tip forces, we will then be able to compare the model data directly with test data. As it stands the data that we get from the blow down is actually more related to the effect most people call the pressure stiffening effect, the model has be constructed in such a way that at a later date we will be able to radially move the rotor towards the bristle pack and obtain the true bristle stiffness under pressure conditions.
We are very encouraged by the data obtained to date; all problems have been solved on a Pentium 4 P.C. with typical solution times ranging from 6 to 20 hours.
We continue to develop the model further with the ultimate goal of correctly simulating all aspects of brush seal operating performance.
A full DOE will be performed once we are happy with the model to enable enough data to be gathered to generate accurate transfer functions for use by all the design staff at Cross.

Conclusions

Brush seals clearly blow-down, this is well demonstrated by the leakage and the torque test data.

There appears to be a strong relationship between the pressure drop across the seal and the magnitude of the blow-down.

Brush seals still blow-down even if the bristles are in contact with the rotor, this is clearly shown by the increase in torque with pressure.

Blow-down is driven by two main factors:-
1) The axial compression of the bristle pack by the delta P.
2) The aerodynamic forces on the tips of the bristles caused by the air accelerating through the gap between the rotor.

The finite element models indicate that the blow down caused by the axial compression effects are strongly influenced by the friction and bristle angle. The back

plate style and fence height also affect the magnitude of this part of the blow down, but to a lesser extent.

Acknowledgements

References

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3. Braun, M., Canacci, V and Hendricks, R. "*Flow Visulization and Quantitative Velocity and Pressure Measurements in Simulated Single and Double Brush Seals"* ASME Paper No 90-GT-217

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